Enhancing Engineering Design Skills through Activity-Based STEM Learning with Environmental Problem-Solving Focus among Vocational Students

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Abstract

This study explores how activity-based STEM learning focused on environmental pollution problems can foster engineering design competencies among vocational students. A mixed-methods design was implemented with twelve first year high vocational certificate-level students in the Mechatronics and Robotics program at a technical college in northern Thailand during the first semester of 2025. The intervention encompassed six instructional units conducted over six weeks (24 hours in total), organized into two phases. Phase 1 (Weeks 1–2) introduced environmental problems, foundational STEM concepts, and basic microcontroller programming and sensor applications using Arduino kits. Phase 2 (Weeks 3–6) engaged students in four hands-on STEM activity stations—Sound (decibel measurement), Soil (moisture measurement), Air (PM2.5 monitoring), and Water (pH measurement)—within a real-world environmental context. Guided by the Engineering Design Process (EDP), students designed, built, tested, and presented monitoring systems integrating microcontrollers and sensors, and subsequently proposed possible solutions to the identified problems. The Engineering Design Skills (EDSs) were assessed using observation rubrics, checklists, group presentations and written reports. Quantitative and qualitative analyses—including time-series tracking and content analysis—revealed consistent skill improvement over four weeks: overall mean scores increased from 2.34 in the first activity to 3.57 in the fourth (scale: 1–4). The EDSs component scores improved across all EDP stages: problem identification (2.50→3.83), solution development (2.25→3.25), design optimization (2.13→3.38), and presentation (2.50→3.83). Qualitative data revealed that students demonstrated greater accuracy in problem identification and a stronger connection to environmental contexts. During solution development, they applied creative and systematic thinking; in the optimization phase, they tested prototypes, analyzed deficiencies, and refined their designs; and in the presentation phase, they exhibited increased confidence, effective use of visual aids, and coherent technical explanations. Their proposed solutions at the end of each activity reflected insightful awareness of environmental issues. These findings indicate that integrating environmental challenge contexts into activity-based STEM instruction can significantly enhance engineering competencies while fostering environmental awareness. This approach may hold potential for preparing vocational students to become innovative problem-solvers aligned with Thailand's sustainable development goals.

Keywords: *Engineering Design Process, Engineering Design Skills, STEM Education, Environmental Education, Activity-based Learning, Vocational Education*

1. Introduction

Developing the Engineering Design Skills (EDSs) is one of the fundamental goals of vocational education, as these skills enable learners to analyze problems systematically, generate feasible solutions, and apply technical knowledge to real-world contexts [1, 2]. In the Thai contemporary vocational programs, students are expected not only to acquire technical competencies but also to demonstrate problem-solving, critical thinking, and communication skills aligned with authentic engineering practices [3]. However, many vocational Thai learners still face difficulties in transferring theoretical knowledge to complex and open-ended problems, particularly when learning activities are not sufficiently connected to meaningful contexts and hands-on design processes [4], similarly found in others [1, 5, 6].

STEM education has been widely recognized as an effective approach for fostering higher-order thinking and practical skills through the integration of science, technology, engineering, and mathematics [5, 7, 8]. A STEM-based approach emphasizes active learning through direct engagement with authentic problems, materials, and data, enabling students to develop engineering practices through iterative design activities [6]. The Engineering Design Process (EDP) refers to the systematic process engineers use to solve real-world problems by applying knowledge and technology to design, test, and refine solutions that meet human needs [1, 5]. When emphasized in STEM learning activities, the EDP provides a structured framework that supports learners in identifying problems, generating possible solutions, testing prototypes, and refining designs based on evidence [1, 9].

In Thai vocational education settings, station-based STEM activities can provide distinct pedagogical advantages by enabling learners to engage with multiple problem scenarios within a structured yet flexible learning environment. Such activities encourage collaboration, systematic thinking, and the development of manipulative skills, as suggested by previous research [10]. Repeated engagement with design tasks across different stations allows students to practice core EDSs in varied contexts, thereby supporting gradual improvement over time [11]. Embedding real-world contexts into STEM activities further enhances learning relevance and student engagement. Environmental monitoring tasks—such as measuring sound levels, soil moisture, air quality, and water quality—provide concrete and observable data that can be directly linked to engineering decision-making [12]. These contexts support students in interpreting data, considering constraints, and designing functional systems, thereby strengthening the connection between engineering concepts and practical applications [13]. Despite growing interest in STEM-based learning in vocational education in Thailand, empirical evidence examining how activity-based STEM instruction influences the development of the EDSs over time remains limited, particularly in vocational contexts [10, 13, 14]. Few studies have systematically tracked students' skill development across multiple design activities using both quantitative and qualitative evidence [15, 16].

Therefore, this study was aimed to investigate the effect of activity-based STEM learning implemented through station-based activities which embedded 5 steps of EDP (asking question and identifying problem; brainstorming; planning and building the prototype; testing and refining; presenting the process and result) on the development of the 4 components of EDSs (defining & delimiting engineering problems; developing possible solutions; optimizing the design solution; presenting the problem-solving process) among vocational students at a vocational school situated in the northern of Thailand. By examining students' performance across four consecutive STEM stations using a mixed-methods approach, this research seeks to provide empirical insights into how structured, context-rich STEM learning environments can support the progressive development of the EDSs.

2. Methodology

2.1 Participants

The participants were twelve first-year higher vocational education students of the Mechatronics and Robotics program at a technical college in northern Thailand. All students voluntarily enrolled in an additional independent elective study course. The participants already had some background in basic electrical circuits, introductory automation, robotics, and elementary programming acquired during their vocational education level. However, prior learning experiences primarily emphasized procedural tasks based on manuals and worksheets, resulting in limited experience with systematic EDP, analytical thinking, exploration of alternative solutions, and iterative prototype development. Therefore, this group was considered appropriate for implementing STEM activities focused on the EDP and for examining the development of the students' EDSs within a vocational education context.

2.2 Learning Context and Intervention

The activity-based STEM was implemented over six weeks (24 hours total) and was structured into two phases. During week 1–2, students were introduced to STEM concepts, environmental issues discussions, and the participle of the EDP. They also reviewed and practiced using microcontrollers, sensors and programming to prepare for subsequent design activities for the later phase. During week 3–6, students engaged in station-based STEM activities working in groups of three across four stations: Sound, Soil, Air, and Water. At each station, students applied the EDP by identifying problems, developing solutions, constructing prototypes, testing and refining the design, and presenting their process and outcomes. Real-world data collected through sensors were used as the basis for engineering decision-making, enabling students to iteratively improve their designs within authentic constraints to acquire 4 EDSs as detailed in Table 1.

Table 1. The EDSs acquired from each activity station (five steps of EDP engaged) across week 3-6

Week / Activity	Station	Defining & delimiting engineering problems	Developing possible solutions	Optimizing the design solution	Presenting the problem-solving process
Week 3 (Activity 1)	Sound Station: Measure noise levels in a factory using sensors and design the alarm system.	Define the noise pollution problem in a factory; delimit the goal of the problem solving; delimit the constraints or criteria of the problem	Brainstorm for creating an alert system using sensor and electronics devices (e.g., LED or buzzer); design possible alarm system models.	Construct the selected sound pollution alert prototype; test and optimize if the sensor reads correctly and the alarm system works well.	Oral presentation and justification, along with written reports, documenting the entire engineering design process and solution development.
Week 4 (Activity 2)	Soil Station: Measure soil moisture in a pineapple field using sensors and design the automatic irrigation system.	Define the soil moisture problem affecting pineapple cultivation; delimit the goal of maintaining appropriate moisture levels; delimit constraints and criteria of the problem solving.	Brainstorm solutions for monitoring soil moisture using sensor and controlling irrigation (e.g. water pumps); design possible irrigation system models.	Construct the selected prototype of the irrigation system; test and optimize the control parameters to improve accuracy and stability of the system.	
Week 5 (Activity 3)	Air Station: Measure PM2.5 level in a bedroom using sensors and activate the air filtering system automatically.	Define the PM2.5 pollution problem in the bedroom; delimit the goal of detecting unsafe air conditions; delimit constraints and criteria of the problem solving.	Brainstorm solutions for creating PM2.5 monitoring using sensor to activate the air filtering system (e.g. fan and purifying filters); design possible air purifying system models.	Construct the selected prototype of the air purifying system; test and optimize the function of the system.	
Week 6 (Activity 4)	Water Station: Measure water quality (pH) in a fishpond using sensors and design a pH controlling system.	Define the water quality (pH) problem in a fishpond; delimit the goal of maintaining pH range; delimit constraints and criteria of the problem solving.	Brainstorm solutions for pH monitoring and controlling (e.g. (acid/base dosing duration); design possible pH maintaining system models.	Construct the selected prototype of the pH controlling system; test and optimize the accuracy and precision the system.	

2.3 Data Collection

To enhance data credibility, multiple data sources were used with three evaluators which comprised of a science teacher, an electronic lecturer and the researcher (physics teacher), allowing for data triangulation across instruments and assessment contexts [17]. The primary instrument was an EDSs Assessment, a four-level rubric checklist evaluating four skill components: defining and delimiting engineering problems, developing possible solutions, optimizing design solutions, and presenting design processes and results [18, 19]. Qualitative data were collected using practice observation, product assessment, and presentation and justification performance. Practical observations focused on students' design practical and teamwork [4, 1]. Product assessments conducted to see the quality and efficiency of products [6, 18]. The presenting skill was evaluated from the oral presentation and written reports [20, 3].

2.4 Data Analysis

Quantitative data were analyzed to see the average scores. Each group was assessed repeatedly week by week to see the developmental patterns over time [21]. Qualitative data were analyzed using content analysis, involving identification of observation records related to the sub engineering design skills, the product evaluations and the presentations. Emerging patterns and trends were identified to support and explain the quantitative findings [22].

3. Results

The results of this study indicate that station-based STEM activities contributed to a continuous improvement in students' EDSs, as evidenced by both quantitative and qualitative data. Overall, average scores across all components of the EDSs increased progressively from the first to the fourth week. This trend suggests that repeatedly engagement in activity-based STEM with EDP supported students' gradual development of engineering practices as shown in Fig.1.

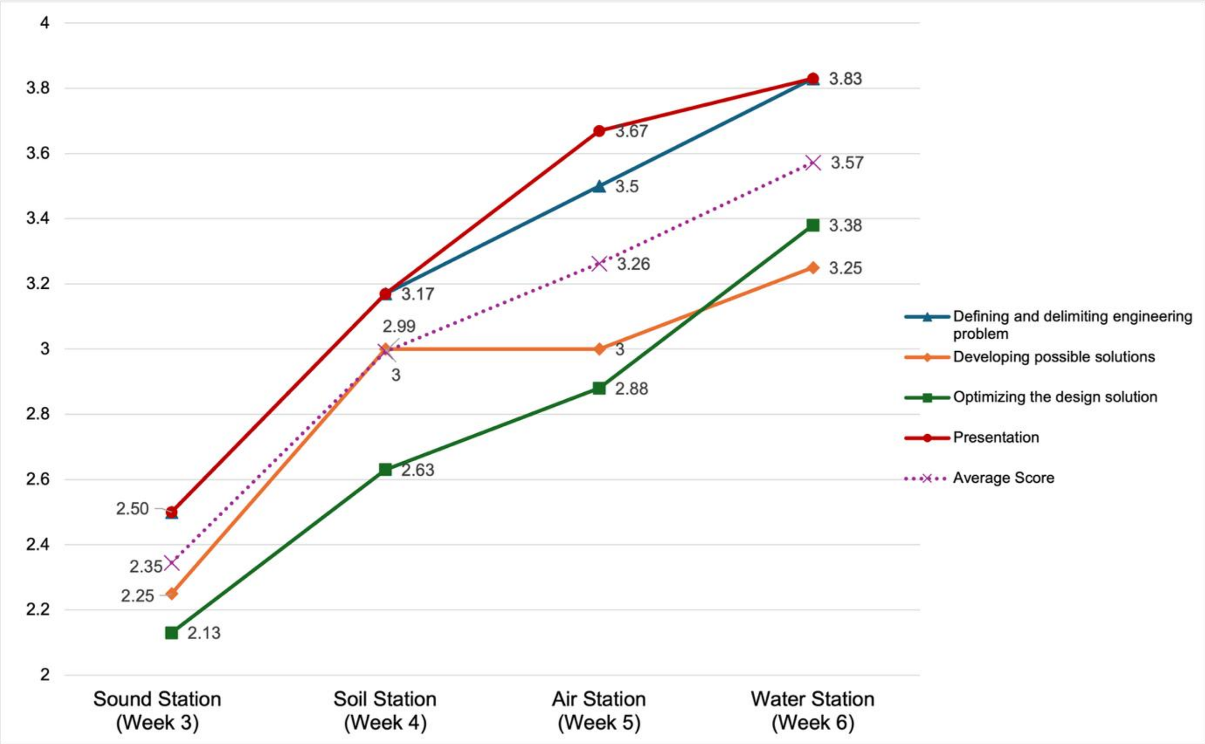

Fig. 1. The EDSs scores progress across the 4 successive weeks

From Fig. 1, it indicated that students' skill in defining and delimiting engineering problem at the Sound Station was higher than the other skills, although the overall performance remained low. The qualitative results indicated that students were able to delimit the noise pollution problem in a factory scenario, but they were not yet able to clearly specify the goal of the problem-solving and to define the constraints or criteria of the problem seemed to be difficult for them to articulate. The instructor then had to play an active role by posing some guiding questions and providing scaffolds to support for clearer problem definition and needed occasionally to help students set the goal and define the constraints more precisely. The following task was to work out for some possible solutions, the result indicated low score at the early stage, students engaged in brainstorming to design an alert system (e.g. flashing light) using sensor that would be activated when the noise level exceeded a set limit. It was seen that students typically proposed simple, single solution design with no alternative methods, typically focused on simple warning systems such as using single LED or only a buzzer alert rather than considering alternative solutions like employing multiple LED colors to indicate the level of noise pollution. Consequently, the instructor had to provide probing questions to encourage students to explore additional options which were slightly sophisticated but useful and practical options. The next task was to optimize the selected design as the prototype, the score was the lowest, the classroom observation result reflected the limited ability of students to test and refine the prototype systematically. Some students even did trial-and-error to construct the system and later founded that the circuit was damaged, resulting that they had to waste time on reconstruction. It's also seen that students primarily relied on trial-and-error parameter adjustment (e.g., randomly changing values) with no data recording or analysis of measurement errors and always requesting help from the instructor to pass through this process. And the final task of the first station was to present the process and results to the classmate and the teacher, and to justify their conclusions. It's seen that the average score was the highest among other skills but still fell within moderate performance level. Students' communication tended to focus mainly on procedural descriptions of circuit assembly and coding rather than on the engineering design itself. The instructor therefore guided students in restructuring their presentations both oral and written reports to place greater emphasis on the EDP and reasoning.

In the second week or station, the Soil Station, the result showed clear improvement compared to the first station, indicating more systematic engagement in the EDP. For defining and delimiting engineering problems, students identified the soil-moisture issue, in a pineapple field scenario, more specifically and they were able to set clearer goals and constraints for problem-solving (e.g., targeting moisture level, sensor placement, feasibility of automation), while the instructor's role was reduced to targeted feedback. For developing possible solutions, students proposed more concrete and structured ideas, including alternative irrigation models (e.g., threshold-based versus timed watering), and used simple flow diagrams to explain how sensor data would trigger system actions; however, some groups still tended to select initial idea without considering other alternative possible ideas and the instructor intervened when the students stuck too long while some groups performed better and better when they started to familiar with the engineer process. It's seen that the students were able to test and adjust the parameters to improve the selected prototype more purposefully, yet challenges remained in controlling variables and handling unstable reading of the sensor across different soil conditions, and some students were testing the system without recording the results. And many cases, the instructor ignored the mistakes to let them learn from their mistakes from other groups' presentation and discussions. The students' oral presentation and written reports became more organized and increasingly improved, although a few still emphasized procedural steps over deeper engineering reasoning. Overall, the Soil Station supported a shift from procedural task completion toward more data-informed engineering practices.

In the Air Station, the skills continued to improve, reflecting stronger engagement. Students were able to frame the PM2.5 issue more clearly by identifying where and when air quality became unsafe and by specifying relevant criteria for monitoring and response in a bedroom scenario. Students generated more feasible system models for air-quality alerts or activate the air filtering systems, and they increasingly justified design decisions using sensor data and contextual constraints. Students demonstrated greater ability to refine prototypes through repeated testing, particularly in addressing unstable PM2.5 readings and improving system reliability through code modification and adjustment of control logic; however, some groups still required instructor prompting to document test results systematically and interpret sensor fluctuations. The oral and written reports showed clearer organization and more frequent use of technical terms, diagrams, and experimental evidence, indicating improved engineering communication. Overall, the Air Station strengthened students' data-driven design reasoning and reinforced awareness of air pollution as a real and measurable environmental concern that can be addressed through engineering monitoring and control systems.

In the last week, the Water Station, it is seen that students' skills continued improving, indicating more independent and mature performance across the EDP employed. Students clearly identified inappropriate pH levels as a specified key for water-quality problem in a fishpond scenario and were able to identify the goals and constraints, including the appropriate pH range and the cautions of using dangerous chemical substance. The students could design more systematic solutions by integrating pH sensing with automatic control, proposing mechanisms for activating acid-base solution pumps based on thresholds and setpoints properly and safely. Students apparently showed strong improvement in iterative refinement by calibrating sensors, controlling variables, reducing pH fluctuation, and improving the stability of the control algorithm through repeated testing and evidence-based adjustment. And finally, students justified and communicated their system with well-structured oral and written reports, supported by numerical data, system diagrams, and clearer explanations of engineering logic, and they demonstrated greater confidence in responding to technical questions. At the discussion part of each written report, students were encouraged to discuss and recognize the value of environmental monitoring in agriculture, contributing to increased awareness of sustainable resource management. It's seen that a real and measurable environmental concern that can be addressed through engineering monitoring and control systems.

4. Discussion and Conclusion

The findings of this study indicate that station-based STEM activities implemented in this study helped enhance the EDSs among a group of Thai vocational students. The gradually increasing of the average scores across all four components—defining engineering problems, developing possible solutions, optimizing design solutions, and presenting design processes and results—similarly found by others [1, 3, 8]. In our context, it is clearly seen that the competencies are best developed through iterative practice in authentic and hands-on learning contexts rather than through existing procedural or instruction-following tasks alone [1, 2]. The results further reveal a clear shift in students' learning behaviors over time. Although, in the early stages, students were not familiar with the EDP for problem solving, they tended to approach tasks through trial-and-error strategies and relied heavily on instructor guidance. As the activities progressed, students increasingly used more acquainted to the better EDP with real data measurement, considering the design constraints, arguing and discussing on the alternative solutions, testing and optimizing and refining their prototypes based on recorded evidence. This progression reflects essential characteristics of the EDP and supports previous research highlighting the role of iterative design experiences in enhancing analytical thinking and problem-solving abilities or overall, as EDSs [4, 7, 10, 19]. In addition, the observed improvement in students' presentation skills underscores the importance of integrating communication tasks into engineering-focused learning activities as an effective key competency in engineering practice [20, 3]. With the integrating the environmental issue, it seemingly indicates that this kind of STEM-based learning also helped highlighted students' capacity to apply data-informed engineering practice in a real-world context and helped enhance their awareness of environmental parameters as an important environmental issue linked to sustainable environmental reservation which can be seen during the process and results presentation and discussion and justification.

In conclusion, this study provides empirical evidence that activity-based STEM learning using station-based activities integrated with the EDP can enhance the EDSs among a class of Thai vocational students. By engaging learners in iterative, data-driven design tasks within structured learning environments, the intervention supported the development of systematic problem-solving, design optimization, and engineering communication competencies. These findings suggest that incorporating station-based STEM activities into vocational curricula can contribute meaningfully to preparing students for professional practice in engineering-related fields.

Future research may build on this work by involving larger samples, applying inferential statistical analyses, or examining the long-term retention and transfer of the EDSs across different vocational disciplines.

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