

Integrating Engineering Design Process in STEM Education: A Project Case Study of Design, Creation, and Programming a Crane's Control Circuit Unit

Konstantinos Asimakopoulos^{1,*}, Thomais Spiliou², and Konstantinos Salpasaranis¹

ABSTRACT

The integration of the Engineering Design Process (EDP) in STEM education has proven to be an effective pedagogical approach, fostering critical thinking, problem-solving, and collaborative skills among students. This paper presents a case study of a project involving the design, creation, and programming of a crane's control circuit unit, utilizing environments and platforms such as Tinkercad and Micro:Bit. The project phases include an introduction to the scientific and engineering concepts of cranes, circuit design, programming, simulation, and physical implementation. This educational methodology not only enhances students' understanding of theoretical concepts but also provides hands-on experience with practical applications. The results of this study highlight the achievements and challenges faced by students during the project, offering insights into the effective integration of EDP in STEM education.

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¹ University of Patras, Greece.

² Ministry of Education, Religious Affairs and Sports, Greece.

* Corresponding Author:

e-mail: kostasasimakopoulos@gmail.com

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1. INTRODUCTION

The rapid advancement of technology and the growing importance of STEM (Science, Technology, Engineering, and Mathematics) education require innovative teaching methodologies. The Engineering Design Process (EDP) is a structured approach that engineers use to develop solutions to complex problems. Integrating EDP into STEM education has been shown to enhance students' critical thinking, creativity, and practical skills [1].

The Engineering Design Process (EDP) is a method widely used in engineering to develop functional products and processes systematically and iteratively. It involves defining problems, brainstorming solutions, designing prototypes, testing, and refining the designs. The integration of EDP in STEM education has been shown to enhance students' engagement and improve learning outcomes [2]. According to Johnson *et al.* [3], integrating EDP in STEM curricula provides a framework for students to apply their knowledge in real-world contexts, thus improving their problem-solving abilities and understanding of interdisciplinary concepts.

Previous studies have shown that project-based learning and EDP are effective in different educational settings. The

National Academy of Engineering and National Research Council [4] report that integrating EDP into STEM projects led to significant improvements in students' problem-solving skills and conceptual understanding. At the same time, the National Center for Engineering and Technology Education (NCETE) was presented successful strategies for incorporating engineering design challenges into science, technology, engineering, and mathematics (STEM) courses in American high schools [5]. Furthermore, researchers have shown that students can engage in engineering design to improve systems thinking that was defined as the ability to understand the components of a system and their interactions and resulting outputs [6] and develop design thinking and computational thinking, as models of thinking, which are important cognitive processes in the twenty-first century [7], [8].

Similarly, UNESCO International Bureau of Education [9] emphasized the benefits of integrated STEM, focusing on the development of technical and collaborative skills. Specifically, UNESCO presents the Kelley and Knowles conceptual framework [2], envisioned as a block and tackle of four pulleys, for integrating diverse aspects of STEM learning. The first pulley is Engineering Design,



where students use and apply mathematics and scientific inquiry skills to design and conduct experiments, evaluating the function and performance of design solutions before constructing a final prototype. The second pulley focuses on Science Inquiry, enabling students to drive their learning by constructing their questions, forming hypotheses, and conducting investigations using standard scientific practices. The third pulley addresses Technological Literacy, which includes both an engineering perspective—designing, making, and using technology—and a humanities perspective, critically analyzing the positive and negative impacts of technology on culture, society, politics, economy, and the environment. The fourth pulley pertains to Mathematical Thinking, involving the analysis and evaluation of design solutions. The rope that ties these pulleys together is the Community of Inquiry, where knowledge is advanced through social discourse involving peers and experts, which helps to focus learning on real-life STEM contexts, regardless of the pedagogical approach.

This study aims to demonstrate how EDP can be effectively integrated into STEM education through a project-based learning approach. The specific project involves designing, creating, and programming a crane's control circuit unit. By engaging students in this hands-on project, the study seeks to achieve the following objectives:

1. Enhance students' understanding of scientific and engineering concepts related to cranes.
2. Develop students' skills in circuit design, programming, and simulation.
3. Foster problem-solving, teamwork, and communication skills.
4. Present the challenges that the students faced during the project and how they were overcome.

A variety of educational tools and platforms have been developed to support the integration of EDP in STEM education. Tinkercad [10] is an online 3D modeling and circuit simulation tool that allows students to design and test their circuits virtually before creating physical prototypes. Another valuable tool is the Micro:Bit, a pocket-sized microcontroller that facilitates hands-on learning in programming and electronics [11].

2. METHODS AND MATERIALS

2.1. Project Overview

The project entailed the thorough process of designing, creating, and programming the control circuit unit for a crane [12]. The phases of the project were meticulously structured according to the Engineering Design Process (EDP), allowing students to gain a comprehensive and hands-on learning experience.

2.2. The Context of the Research-Participants

The study included 21 students in a first-grade class at a Vocational High School. The research was conducted during the Project Research in Technology and Computer Science courses over 16 weeks, from January to April 2024. The students were divided into six groups of 3–4

students. One student in each group acted as the secretary and took notes. The groups were selected randomly from the eight sections of the first grade. For their assignment, the students were asked to design circuits and program a mechanism to remotely lift people to and from a theater stage [12].

2.3. Implementation of the Method

The Engineering Design Process (EDP) in STEM education consists of systematic steps that guide students from identifying a problem to implementing a solution. According to Peters-Burton, Johnson, May and Moore, the EDP can be broken down into six specific components: defining the problem, learning about the problem, planning a solution, trying the solution, testing the solution, and deciding whether the solution is good enough [13]. According to this implementation, the learning cycle consists of the five parts Engage, Explore, Explain, Elaborate, and Evaluate of the 5Es Instructional Model [14]. The aforementioned methods are being combined and integrated with the Computational Thinking (CT) concepts [15].

This unit outlines a research activity in which students design, program, and build a control system for a crane using TinkerCad and Micro:Bit. The project is divided into three phases to align with the stages of EDP.

2.3.1. Phase 1: Scientific and Engineering Concepts of Cranes-Familiarization with Tinkercad

1. *Define the Problem:* The project began with an introduction to the scientific and engineering principles underlying crane operation. Students learned about the mechanics of cranes, including forces, torque, and equilibrium, as well as the different types of cranes and their applications. Students are tasked with creating a control system for a crane that uses two DC motors: one for rotational movement and one for lifting and lowering the hook.
2. *Learn About the Problem:* Students begin by exploring the TinkerCad interface to understand the environment and tools available for their project. Activities include:
 - *Introduction to TinkerCad:* Overview of the environment, account creation, available categories, and basic functions.
 - *Programming the Micro:Bit:* Familiarization with the block-based programming environment. Students create simple programs incorporating basic programming techniques and event-driven programming concepts.

2.3.2. Phase 2: Learning Basic Programming and Circuit Design

1. *Plan a Solution:* Students delve into basic programming concepts such as variables, loops, and conditions, and learn about the functioning of servo and DC motors. They plan how to integrate these elements into their crane control system.
2. *Try the Solution:* Students use TinkerCad to design, program, and simulate real circuits. Specific activities include:

- *Servo Motor Simulation:* Connecting and programming servo motors with the Micro:Bit to understand their capabilities and limitations.
- *DC Motor Simulation:* Connecting and controlling DC motors, experimenting with polarity, and exploring the differences between servo and DC motors.

2.3.3. Phase 3: Implementation and Optimization

1. *Test the Solution:* Students transition from virtual simulations to physical construction. They assemble the crane control system using the Micro:Bit, motor controller, and DC motors. Students integrated their control circuits into a small-scale crane model. They ensured that the crane's movements could be controlled accurately through the programmed Micro:Bit. Key activities include:

- *Circuit Design and Implementation:* Connecting two DC motors to the motor controller and Micro:Bit.
- *Programming:* Developing and refining the control system code in TinkerCad.
- *System Construction:* Assembling the physical components required for the crane control system.
- *Program Download:* Transferring the developed program from TinkerCad to the Micro:Bit microcontroller.

2. *Decide Whether the Solution is Good Enough:* Students test their constructed system to evaluate its performance. They monitor the crane's operations, identify any issues, and optimize the code for smooth functioning. Specific activities include:

- *Testing and Optimization:* Running the system, making adjustments, and ensuring optimal performance.

2.4. Computational Thinking

These aforementioned methods are being combined and integrated with the concepts of Computational Thinking (CT).

One definition of Computational Thinking (CT) is given by Wing [15], as “a way of solving problems, as the example of computer scientists. Thinking like a computer scientist, is more than programming. Computational thinking is the fundamental concept of solving problems, designing systems, and understanding human behavior.”

It is well known that computational thinking will influence every person in every field of anything might try to succeed at. Having a clear sense of the technology and the science of computing, we need to pay attention to the three drivers of our field: science, technology and society, according to Wing [16], which are basic concepts in STEM Education.

A second definition of CT, according to CSTA&ISTE [17], is a problem-solving process that is characterized by some of the following features:

- Problem definition in a way that allows the use of computer and other tools to solve problems.
- Logical arrangement and data analysis of the problems
- Data representation through “Abstraction,” such as models and simulations.
- Automated solutions through “Algorithmic Thinking,” following a sequence of clearly defined steps-actions.
- Identification, analysis and implementation of possible solutions to achieve greater effectiveness.
- The effective problem-solving process is generalized and transformed to other problems.

The important work of Papert [18] and his “descendants” in Computer Science (CS) education, as Resnick [19], can be the proposed carriers of the educational model scheme for introducing Computer Science concepts in the classroom. For the implementation of constructionist theory, both Logo-like programming environments, block-based programming environments and computing systems such as Tinkercad [10] and Micro:Bit [11], respectively, have a significant impact.

According to this schema, Resnick [19], [20], proposed a creative learning pathway, of four P's (Project, Peers, Passion, Play). Essential base for people to learn is to work on meaningful Projects, generate new ideas, design prototypes, and refine them iteratively. Peers are also a social activity, with individuals sharing ideas, collaborating on projects, and developing on each other's work. Passion leads to longer and harder work, persistency against obstacles, and increased learning in the process. Playfulness. Playful experimentation involves trying new things, tinkering with materials, testing boundaries, taking risks, and iterating again and again [20], [21].

2.5. Materials (Educational Tools)

The design of the research included the free web-based modelling software Tinkercad which allows the design of the required motor wiring with the Micro:Bit microcontroller, programming, and simulation of the operation of the structure.

2.5.1. About Micro:Bit

The Micro:Bit (version 2) is a microcontroller developed by a group of companies led by the BBC in the UK in 2015 to teach computer science, Fig. 1. It is a small, credit card-sized board that includes an ARM M processor (Arm Cortex-M4 32 bit processor with FPU), two physical buttons labeled A and B, a 5 × 5 led matrix for displaying letters and numbers, is equipped with a light sensor, a combined accelerometer and magnetometer chip that provides 3-axis sensing and magnetic field strength sensing, thermometer, speaker/buzzer, microphone, General Purpose Input/Output Pins that offer connection with external components for input (sensors, buttons, etc.) or output (activators, motors, LEDs etc.). It, also, supports wireless communication via radio waves and Bluetooth

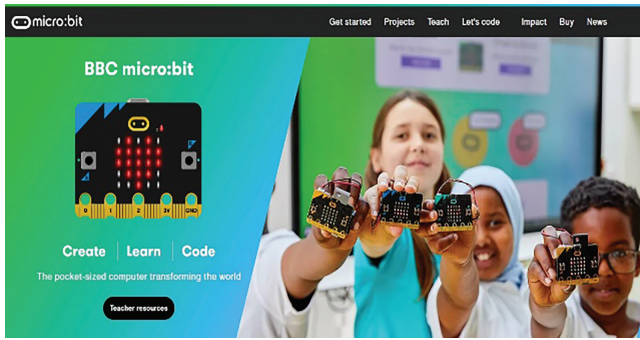


Fig. 1. Micro:Bit environment [7].

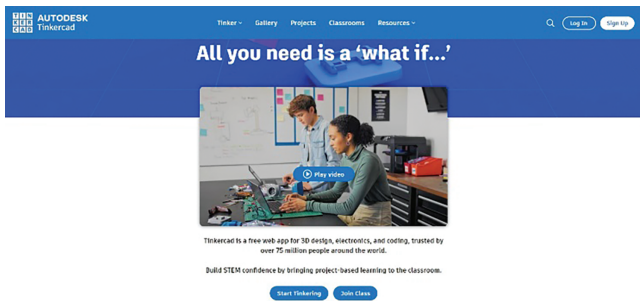


Fig. 2. Tinkercad environment [6].

[11]. Finally, it has a 3 V power supply terminal and a ground (GND) terminal.

The Micro:Bit can be programmed with programming environments such as MakeCode [11], TinkerCad [10], block-based programming environments, the Python programming language or the Javascript programming language. In this study, the TinkerCad [10] environment has been used.

2.5.2. About Tinkercad

TinkerCad, Fig. 2, is a free online environment for 3D modelling and simulation. It is composed of four sub-tools: 3D Design, Circuits, Codeblocks, and SimLab for 3D design models, Circuit design, Circuit Programming and Circuit simulation of virtual electronic circuits, 3D Design by Coding and simulation of animated 3D models that runs in a web browser, respectively [10].

3. RESULTS

In this section, the steps of the learning pathway of the project-based learning implementation by the groups of participating students according to the EDP design [13] and the three educational phases will be further analysed.

The entire training process, including the construction of the project, was carried out over sixteen (16) weeks. Table I presents the learning pathway per week, Project Phase, EDP Stage (Define, Learn, Plan, Try, Test, Decide) according to Johnson *et al.* [13] and activities.

3.1. Phase 1: Scientific and Engineering Concepts-Familiarization with Tinkercad

- *Presentation of Tinkercad:* Introduction to the environment and tools.

- *Activity D1:* Students became familiar with the 3D design environment by creating a house.
- *Activity D2-Robots:* Students discovered more possibilities/tools in the 3D design environment by creating a robot.
- *Activity D3-Balance:* The students discovered the simulation possibilities (physical laws-gravity) offered by the Tinkercad environment [10].

3.2. Phase 2: Learning Basic Programming and Circuit Design

Introduction to Tinkercad Circuits:

- *Activity A1:* Blinking a light on the Micro:Bit led matrix: Our aim is to program the Micro:Bit so that a light flashes on the built-in 5×5 display that it has.
- *Activity A2:* Show text on the Micro:Bit and press its buttons: Our task is to program the Micro:Bit to display text on its built-in 5×5 led matrix and pressing the A and B buttons to select the text to be displayed.
- *Activity A3:* Displaying numbers and pressing buttons: We aim to program the Micro:Bit to display numbers on its matrix which will change when the A and B buttons are pressed.
- *Activity A4-Messaging:* Micro:Bit has a built-in radio communication function. We aim to program 2 Micro:Bit so that they exchange messages with each other when the A or B keys are pressed, Fig. 3.
- *Activity A5-Motors (I):* We aim to connect a motor to the Micro:Bit and control the movement of its blade by pressing the A and B buttons, Fig. 4.
- *Activity A6-Motors (II):* we aim to connect a DC motor to the Micro:Bit and control the movement of its gear, Fig. 5.
- *Activity A7-Motors (III):* our objective is to connect two DC motors to the Micro:Bit and control the movement of their gears, Fig. 6.
- Implementation in Micro:Bit.

3.3. Phase 3: Implementation and Optimization

- *Activity B1-Crane control:* Our objective is to connect the Micro:Bit to a toy crane and control its operation by replacing the toy controller. The toy has two built-in DC motors: one for movement on the horizontal axis and one for movement on the vertical axis, that of the weight lifting hook.
- *Load Lifting Activities:* First, we will start a new project (circuit design) in the TinkerCad environment. We will design the circuit with which we will replace the crane's remote controller.

We will program the Micro:Bit in order to display the icons sequentially at startup and set the polarity on outputs 13, 14, 15 and 16 where the motors are connected to 0 (LOW).

Next, we will program the buttons that will control the movements of the crane.

TABLE I: TEACHER'S DIARY

Weeks (Project phases)	EDP stages	Activities
1–4 (Phase 1)	Define the problem, learn about the problem	Scientific and Engineering concepts-familiarization with Tinkercad
5–14 (Phase 2)	Plan a solution, try the solution	Learning basic programming and circuit design
15–16 (Phase 3)	Test the solution decide whether the solution is good enough	Implementation and Optimization

Άσκηση

1. Προγραμματίστε το Micro:Bit2 ώστε να στέλνει κι αυτό ένα μήνυμα στο Micro:Bit1 με το πάτημα του κουμπιού A.
2. Προγραμματίστε το Micro:Bit1 ώστε όταν πατήσουμε το κουμπί B να στέλνει το μήνυμα «Hi!». Όταν το Micro:Bit2 λάβει αυτό το μήνυμα να εμφανίζει στην οθόνη του ένα icon της επιλογής σας, διαφορετικό από το .
3. Προγραμματίστε το Micro:Bit2 ώστε να στέλνει ένα διαφορετικό μήνυμα στο Micro:Bit1 με το πάτημα του κουμπιού B.
4. Προγραμματίστε το Micro:Bit1 ώστε με το πάτημα του κουμπιού A+B να καθαρίζουν οι οθόνες και των δύο Micro:Bit.

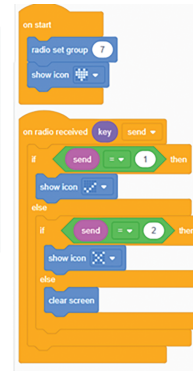
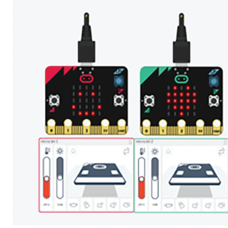


Fig. 3. Messaging with Micro:Bit's built-in radio communication.

Άσκηση

1. Προγραμματίστε το Micro:Bit ώστε με το πάτημα του κουμπιού B, να στρέφεται το πτερύγιο του σερβοκινητήρα κατά 180 μοίρες. Τι παρατηρείτε σχετικά με τη θέση του πτερυγίου του σερβοκινητήρα κάθε φορά που πατάτε το κουμπί A ή B; Πώς μπορούμε να ορίσουμε την αρχική θέση του πτερυγίου του σερβοκινητήρα;
 2. Προγραμματίστε το Micro:bit ώστε κάθε φοράτο πτερύγιο του σερβοκινητήρα να επανέρχεται στην αρχική του θέση. Πόσος πρέπει να είναι ο χρόνος αναμονής ώστε να γίνεται εμφάνης και κατανοητή η στροφή του πτερυγίου;
 3. Προγραμματίστε το Micro:bit ώστε το πτερύγιο να στρέφεται κατά 45 μοίρες και να επανέρχεται στην αρχική του θέση με το τράνταγμα του Micro:bit.

Πρόεταση

5. Ας χρησιμοποιήσουμε μια μεταβλητή **var** για να ελέγξουμε τον ρυθμό περιστροφής του πτερυγίου με τα παρακάτω μπλοκ:

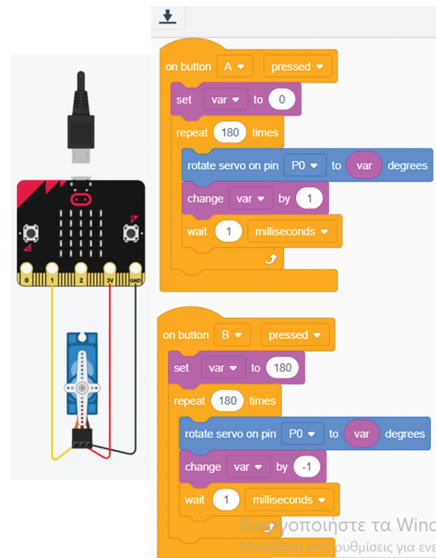
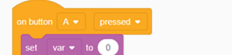


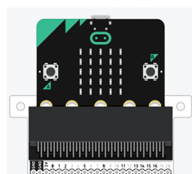
Fig. 4. Controlling servo motor with Micro:Bit.

Άσκηση

4. Προγραμματίστε το Micro:Bit ώστε όσο κρατάμε πατημένο το κουμπί A το γρανάζι να στρέφεται δεξιόστροφα. Τι συμβαίνει όταν αφήσουμε το κουμπί A; Πώς μπορούμε να διορθώσουμε το πρόβλημα;
5. Προγραμματίστε το Micro:Bit ώστε όσο κρατάμε πατημένο το κουμπί B το γρανάζι να στρέφεται αριστερόστροφα.

Δραστηριότητα A7 – Κινητήρες (III)

Σκοπός μας είναι να συνδέσουμε στο Micro:Bit δύο DC κινητήρες και να ελέγξουμε την κίνηση του γραναζιού τους.



Στο Micro:Bit, έχουμε τη δυνατότητα να συνδέσουμε μια πλακέτα επέκτασης ώστε να έχουμε περισσότερες εισόδους/εξόδους. Οι λειτουργικές εισόδους/εξόδους είναι αυτές που υποδεικνύονται από τους αντίστοιχους αριθμούς.

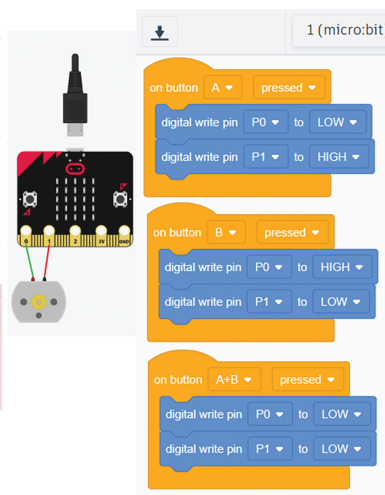


Fig. 5. Controlling DC motor with Micro:Bit.

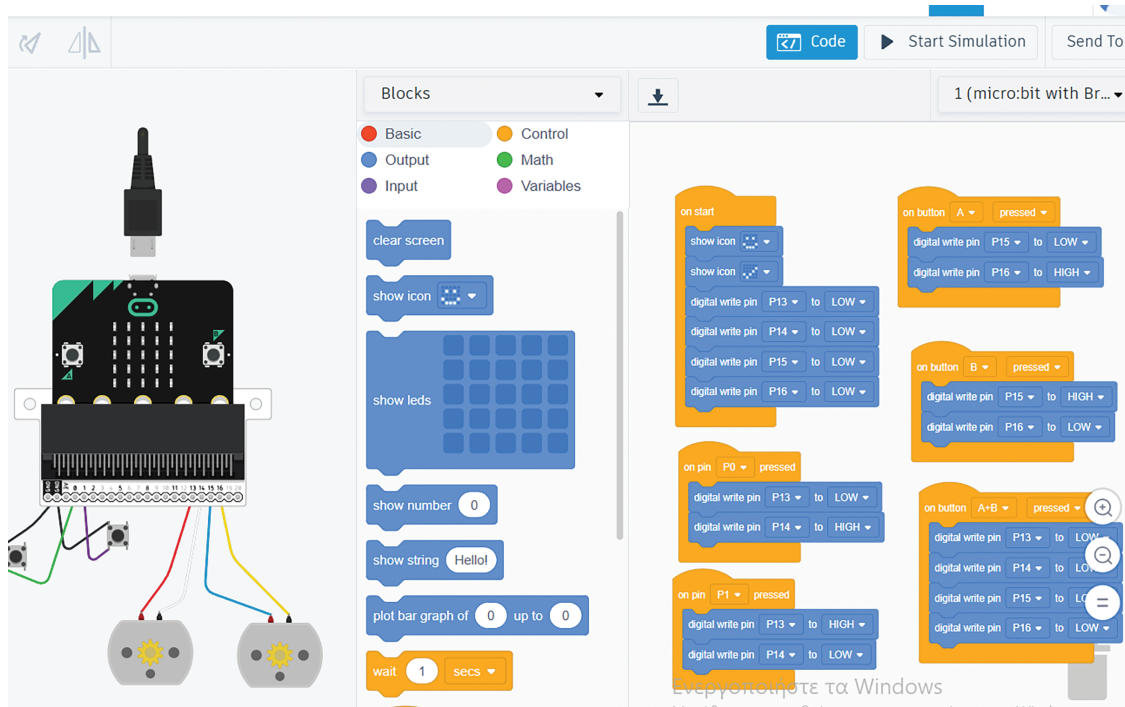


Fig. 6. Controlling two DC motors with Micro:Bit and external buttons.

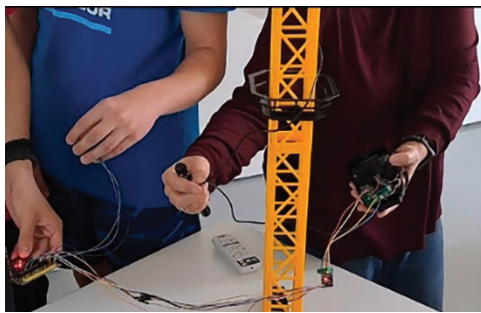


Fig. 7. Controlling the crane with the Micro:Bit controller.



Fig. 8. Crane project with Micro:Bit's functionality.

The next step, is to create our controller with Micro:Bit. In the creation process, we will follow the schematic of the circuit we designed in the Tinkercad environment with the connection of the motors to the expansion board to insert the motor driver.

Finally, the project ends with the control and operation of the crane by the participated students, Figs. 7 and 8. Regarding some quantitative conclusions we can report that phase 1 activities were successfully finished by all 6 groups. Two groups in phase 2 received assistance from peers who had finished the tasks more quickly because they required a bit more time to finish them. For the crane control system, each of the six groups created a solution. During phase 3, all six groups succeeded in assembling the crane control components. Excited about the crane's operation, they experimented with their art crafts. Two groups had to refine their models. Further questions and project expansions arise such as that of creating a crane swarm by wireless communication of Micro:Bits via radio group frequencies.

4. DISCUSSION AND CONCLUSION

The incorporation of EDP into this STEM project offered a comprehensive educational experience, blending theoretical knowledge with hands-on application. This approach allowed students to cultivate critical thinking and problem-solving skills, which are essential for their future careers in STEM fields. The utilization of platforms such as Tinkercad and Micro:Bit contributed to a seamless learning process, rendering complex concepts more approachable and engaging for the students. Based on the findings, several recommendations can be made to improve the integration of EDP in STEM education:

- *Enhanced Training for students and educators:* Providing comprehensive training on EDP and the use of educational tools like Tinkercad and Micro:Bit can improve the effectiveness of project-based learning.
- *Incremental Complexity:* Introduce projects with incremental complexity to help students build their

skills gradually, reducing frustration, and enhancing learning outcomes.

- *Collaborative Learning*: Encouraging teamwork and collaboration among students can foster peer learning and improve problem-solving competences.
- *Iterative Testing and Feedback*: Incorporating iterative testing and regular feedback sessions can help students identify and address issues early, improving the overall quality of their projects.

The project yielded several positive outcomes. Students demonstrated a strong understanding of the scientific and engineering principles of cranes. They successfully designed, simulated, and implemented control circuits, showcasing their ability to apply theoretical knowledge to practical tasks. The use of Tinkercad and Micro:Bit facilitated a seamless transition from virtual simulations to physical prototypes, enhancing students' confidence in their technical skills.

Despite the overall learning achievements, students encountered several challenges. Programming the direction and speed of the motors proved to be difficult for some teams, requiring additional learning scaffolding, troubleshooting and iterative testing. Additionally, ensuring the physical stability and accurate movement of the crane posed challenges, highlighting the importance of precise circuit design and robust programming.

CONFLICT OF INTEREST

Authors declare that they do not have any conflict of interest.

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