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PAPER

Developing a Mobile Game Application to Enhance Learning Experience in Programmable Logic Controller (PLC) Wiring beyond the Laboratory

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ABSTRACT

In the field of automation technology education, the primary emphasis is on instructing students in the use of programmable logic controllers (PLCs). Practical training for beginners includes sessions on wiring and programming. However, the training on wiring lacks resources for additional practice outside the laboratory. Recognizing the potential of mobile devices and digital game-based learning, this study aims to create a mobile game app for practicing basic PLC wiring at any time and in any location. The study also seeks to examine the impact of using the game app on student performance and user satisfaction. The game app underwent expert assessment and received a high suitability rating, garnering an overall score of 4.43. Subsequently, it was employed in an experiment involving an experimental group comprising 18 students and a control group consisting of 22 students. To address non-normal data, we utilized both parametric and non-parametric methods to ensure more robust data analysis. The study found that both the independent sample t-test and the Mann-Whitney U test yielded consistent results, with p-values of 0.009 and 0.01, both below 0.05. This led to the conclusion that additional practice with the game app improved students' performance in wiring. The user experience received positive feedback, with an overall score of 4.25. Based on the results, we consider this game app to be an effective learning tool that can enhance student performance and the learning experience in basic PLC wiring.

KEYWORDS

mobile game application, educational game, programmable logic controller (PLC), wiring

1 INTRODUCTION

In today's industrial work environment, it is likely that everyone is familiar with programmable logic controllers (PLC). A PLC is an electronic device used to control the operations of machines, equipment, and other devices in the production process.

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It allows them to run automatically through programmed control commands instead of using traditional electrical or pneumatic circuits [1]. As PLCs have continuously grown and evolved to become the preferred option for automation in production environments, as well as in other sectors such as the automotive and chemical industries [2], [3], the ability to work with PLCs has become a necessary skill for various professions, from engineers who design the systems to technicians who maintain them.

Many educational institutions, both at the university and vocational levels, have recognized the need for PLC content in the industrial sector. As a result, they have integrated PLC content into various courses in related fields, such as electrical engineering [3], mechanical engineering [4], and chemical engineering [5]. The fundamental content for teaching PLCs at the basic level typically includes basic information about PLCs, their operational principles, connecting them to other devices, and the basics of programming commands to control automatic operations. In practical training, students need to use relatively expensive equipment and tools, such as PLC trainers, PLC training kits, or other similar items, to practice wiring and programming. Despite the endeavors of multiple studies, as referenced in [6] and [7], that have advocated for the creation of PLC trainers with a reduced production cost per set in comparison to commercial PLC trainers, the accessibility of such trainers persists as limited and insufficient to meet the needs of numerous students in educational institutions. Furthermore, the restricted time allocated for hands-on training in laboratories is often inadequate for students to achieve effective learning, given the individual differences in learning potential. Furthermore, during emergency situations, such as the recent COVID-19 pandemic, it is even more challenging for students to access laboratories and have enough practical training time.

The concept of remote laboratories and virtual laboratories is often utilized to address the challenge of limited lab time and equipment. Most of the related studies, such as those referenced in [8] and [9], have focused on designing systems that enable students to access and learn from the facilities at any time and from anywhere. However, these systems only focus on practicing PLC programming. However, only one study, as presented in [10], has introduced a virtual interaction-based PLC training system. This system enables students to remotely access and practice both wiring and programming. In addition, there are general mobile applications such as the "TimeCounts" app [11] and the "eLogicum" app [12] for PLC programming practice. However, there is a noticeable absence of apps dedicated to wiring practice. This apparent lack of resources underscores the inadequacy of offering students the chance to practice PLC wiring without the limitations of time and location. The persistent challenge for students, particularly those with minimal background in electrical wiring, stems from the scarcity of practice opportunities. This scarcity hampers their ability to develop the necessary skills in PLC wiring.

At present, learning through mobile apps on smart devices, such as smartphones and tablets, is well-suited to the lifestyle of modern learners, as these devices are almost always carried with them. Utilizing a mobile app as the primary tool for learning, combined with digital game-based learning as its instructional approach, has the potential to enhance student engagement and motivation, ultimately leading to improved learning outcomes [13]. Considering these advantages, this study aims to develop an educational game app for smartphones and tablets. The app will serve as an interactive learning tool, providing students with the flexibility to practice PLC wiring at their own pace, anytime and anywhere. This will enable them to enhance their learning. In addition, we will examine the impact of using the developed game app on student performance in PLC wiring as well as user satisfaction.

2 LITERATURE REVIEW

2.1 Digital game-based learning

Digital game-based learning is an approach that promotes learning while providing enjoyment through playing games on various digital devices, including computers, game consoles, smartphones, and tablets. This approach involves integrating or embedding educational content into the game appropriately [13]. Over the past two decades, it has gained widespread adoption across various subject areas and can contribute to students' acquisition of knowledge, skills, and attitudes, as well as the promotion of their learning motivation, engagement, and interest [14–16]. In addition to its potential to support learning, this approach offers several advantages, including flexibility in learning time and location, the ability to learn at one's own pace, a safe simulated learning environment, the option to share games with an unlimited number of students, and the opportunity for unlimited repetitions [17]. However, the development of educational games presents its own set of challenges. They are expected to effectively convey instructional content while engaging students in meaningful learning activities within the games. The authors in references [18] and [19] emphasize the importance of game design in influencing the effectiveness of this approach. The design of games has an impact on their potential for learning.

2.2 Game mechanics design for learning

As described in [20], game mechanics consist of the rules, structures, and procedures that direct players in achieving the game's objectives and regulate the game's functions, while game elements encompass the various components and features used to execute and enhance the game mechanics, enhancing the player experience. They are closely interconnected and essential to every game, whether digital or analog, and play a crucial role in game design, exerting a significant influence on player engagement, motivation, and learning outcomes.

For educational purposes, game mechanics and elements should be designed to support the achievement of the intended learning objectives while maintaining a balance between the difficulty of the learning tasks and the learner's enjoyment. Good design will help learners more easily achieve the flow state, in which they experience deep involvement and satisfaction with learning activities to the extent that they lose awareness of the time, effort, and repetition inherent in the learning process [21]. Based on references [22] and [23], four main antecedents that can contribute to the state of flow should be taken into consideration for the design, as follows:

1. **Clear goals:** The game's objectives should be clearly defined and aligned with the learning goals, offering a structured and directional framework within the game. They should be prominently displayed at the beginning of the game, ensuring that they are easily understandable and readily accessible to learners. Furthermore, the main objectives can be broken down into sub-goals that are introduced at a suitable pace, fostering a sense of accomplishment and success as learners advance.
2. **Optimal challenges:** In-game challenges should strike a balance, avoiding excessive difficulty that could lead to learner frustration and discouragement, while also steering clear of excessive ease that might result in learner boredom.

They should adapt to the evolving abilities and knowledge of the learners, as well as to the increasing amount of time spent in the game. For example, as learners progress to higher levels, challenges can be adjusted to include more obstacles, fewer hints, shortened time limits, or increased content complexity.

3. **Immediate feedback:** Learners should receive prompt feedback on their performance and the consequences of their actions. This should be coupled with clear explanations, additional guidance, and access to relevant resources. Information about the next steps to take or the available options should be easily accessible to prevent any confusion or disorientation. Furthermore, it is crucial to provide feedback on learners' progress, enabling them to assess the extent of their acquired knowledge and abilities as well as what remains to be accomplished. This can be achieved through various methods, such as presenting statistics in different formats, using progress bars, unlocking levels upon successful completion, or employing other graphical or visual representations.
4. **Focus and concentration:** Reducing distractions is essential for helping learners maintain focus. This can be achieved by simplifying user interfaces to match the learners' skill levels and by removing unnecessary elements that might distract their attention. Additionally, designing the learning experience to incorporate a suitable level of competition, whether it's competing against oneself, against the game, or against other learners, can be beneficial. Encouraging collaboration with peers can also help improve focus levels.

The thoughtful design of game mechanics and elements, considering these four aspects mentioned above, can create an effective, enjoyable, and engaging learning experience. Recognizing their potential to enhance engagement and learning, game mechanics and elements have been increasingly applied in non-game contexts over recent years, a concept widely known as gamification. This involves integrating these elements into teaching and learning activities [24], [25], online learning platforms [26], [27], questionnaires [28], and various other areas.

3 GAME APPLICATION DEVELOPMENT

In this study, our objective was to develop an educational mobile game called the "PLC Wiring App" to help users practice PLC wiring. The prototyping process for this game app involved meticulous design, development, and expert evaluation, which included the following key details:

3.1 Training topics

A panel of five experts, each with a minimum of five years of experience in teaching basic PLC concepts, was invited to contribute to defining the scope of training content for the development of the PLC Wiring App. The group comprised four lecturers from different universities and one skilled labor instructor from the Department of Skill Development, Ministry of Labor. They collectively concluded that the app should offer essential training for novice learners to practice connecting PLC input/output modules with various input and output field devices. This training is based on the concepts of sinking (NPN) and sourcing (PNP), using wire colors according to the IEC 60227 International Standard. The chosen PLC for the app development is the Mitsubishi MELSEC iQ-F FX5U series, specifically the FX5U-32MR/ES model.

This model is specified as a 24VDC sink/source input type with relay output. To prevent confusion or misunderstanding among inexperienced learners, the game was designed with two distinct modes. The first mode focuses on sink-type circuits for both PLC input and output modules (sink I/O circuits), while the second mode focuses on source-type circuits (source I/O circuits). Both modes cover similar training content, which is divided into a total of eight topics, as outlined in Table 1.

Table 1. Training topics in the PLC Wiring App

Unit	Training Topic
1	AC power supply and circuit breaker wiring
2	External power supply wiring
3	24VDC input circuit configuration
4	24VDC output circuit configuration
5	24VDC input and output circuit configuration
6	24VDC input and output circuit configuration with more and diverse input/output devices
7	24VDC and 220VAC output circuit configuration
8	24VDC and 220VAC output circuit configuration using external relay

3.2 Game mechanics and elements

The structure of the PLC Wiring App can be more easily explained through a simplified diagram, as shown in Figure 1. The game is designed with the understanding that players can always return to the previous page at any time.

In each game, players will receive instructions on how to complete the circuit connections based on the game's objectives. For example, players may be instructed to connect a normally closed (NC) push-button switch to the PLC through input X02. Once the players understand the instructions, the gameplay begins with selecting the color of the first wire to be connected between two devices. After that, they choose the desired connection point on any device, where each button represents a significant terminal on each device for wire connections. If the wire is connected using a color that does not comply with the IEC 60227 International Standard, a sound effect and a message will indicate that the connection is incorrect, prompting players to review the topic of wire colors. Players have two options: they can either select a new wire color or choose a new connection point. Once they successfully connect the wire to the first device, a message will prompt them to select the next connection point on a second device. If the terminals connecting the two devices are not matched correctly, a sound effect and a message will indicate an incorrect connection, prompting players to review their device connections. Again, they have two options: selecting a new connection point on a second device or canceling the current wire connection and starting with a new wire instead. When the wire is successfully connected between the two devices, a sound effect and a message will indicate a correct match, and the wire connection will be clearly illustrated on the game screen. In the next step, players begin by selecting the color of the second wire and continue until they successfully connect the second wire between the two devices. They repeat this process until they achieve a complete PLC wiring circuit, as instructed by the game. Players will be congratulated with a sound effect and a pop-up window when they successfully complete each game.

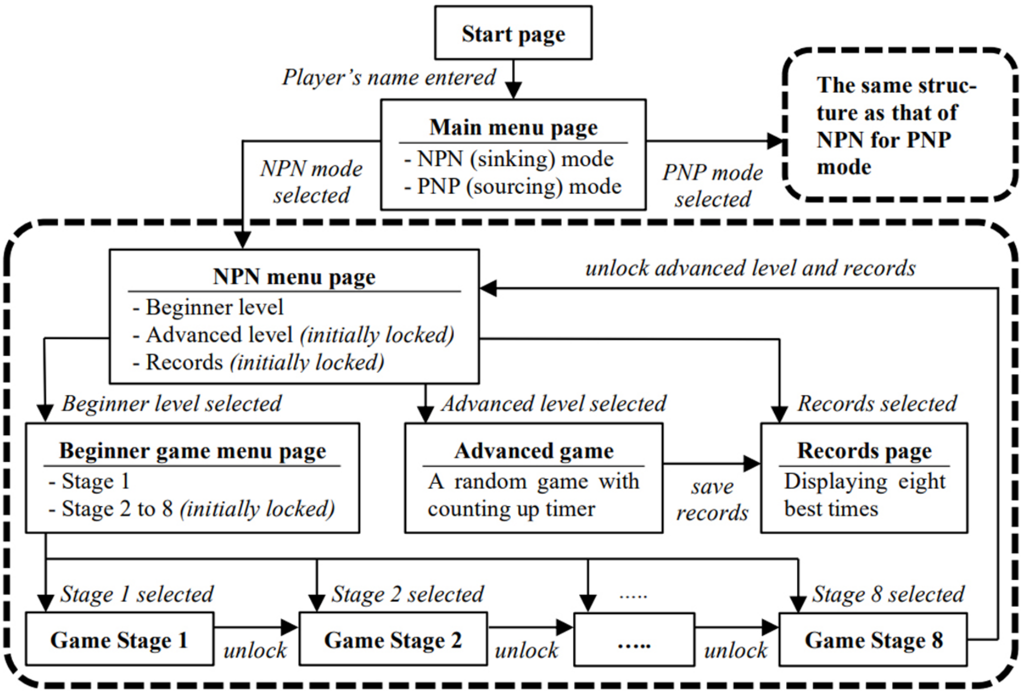

Fig. 1. Simplified structure of the PLC Wiring App

In the PLC Wiring App, the following key game elements related to the mechanics were implemented:

1. **Levels:** The game is divided into two levels: beginner and advanced. The beginner level consists of eight stages, organized in increasing order of complexity, corresponding to the training topics outlined in Table 1. Each stage needs to be successfully completed to unlock the next stage. On the other hand, the Advanced level features a single main game that is randomly generated from a pool of subgames with similar levels of complexity.
2. **Goals:** Two main goals have been established. Firstly, players must complete all stages in the Beginner level to unlock the Advanced level. Secondly, players are encouraged to aim for the fastest completion time possible at the Advanced level.
3. **Rules:** The guidelines and instructions on how to play the game are clearly explained, ensuring easy understanding for players. The instructions will be easily accessible and available for reference at any time during gameplay, including the game objectives.
4. **Time:** A count-up timer is used in the Advanced level. This game will challenge players to effectively manage their time and determine how quickly they can complete it.
5. **Leaderboards** either personal or global, can add an extra layer of competition for players. In this study, there were limitations in terms of budget and available testing equipment. Therefore, a preliminary design was created to include a personal leaderboard that displays the player's eight shortest completion times in the Advanced level. This feature allows each player to track their own progress and work towards improving their performance.
6. **Immediate feedback:** After players perform each action in the game, the system will provide them with brief messages guiding them to the next steps of gameplay. Additionally, sound effects will indicate whether the wiring is correct

or incorrect. When a game stage is successfully completed, a congratulatory window will appear to celebrate the player's accomplishment.

3.3 Development tools

Game engines have become widely popular as versatile tools for game development across various platforms, including consoles, computers, and smart mobile devices. They offer features that facilitate the integration of various game components, such as graphics, sound systems, and scripting languages [29]. In the case of the PLC Wiring App, Unity (version 2020.3) was used as the game engine, while Microsoft Visual Studio 2019 was utilized for scripting in the C# language. While Unity enables users to create game apps for both the iOS and Android platforms [30], targeting iOS specifically can result in additional expenses and restrictions because of budget limitations and device availability. Therefore, the original version of the PLC Wiring App was only compatible with Android mobile devices with a minimum API level of 24 (Android 7.0).

3.4 Expert evaluation

Two expert groups evaluated the prototype of the PLC Wiring App. The first group consisted of five experts with at least five years of experience in teaching PLCs at the basic level. They were invited to evaluate the game app based on its content, which consisted of nine items, and its usefulness, which consisted of five items. The second group consisted of five digital media experts who are lecturers in computer education or computer science and have at least five years of experience. They were invited to evaluate the game app in terms of design, which included 10 items, and operation, which also included 10 items. The questionnaires used in the evaluation employed a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). The combined total number of items in both questionnaires was initially 36. The questionnaires were developed based on modifications from previous studies [31], [32]. The index of item-objective congruence (IOC) was used to evaluate the content validity of the items, and three experts in educational technology assessed them. Two items with indices below 0.5 were eliminated. As a result, a total of 34 items remained with an IOC between 0.67 and 1.00, indicating that all items could be utilized.

4 EXPERIMENTAL DESIGN

An experiment was conducted to investigate the impact of using the newly developed PLC Wiring App on student performance in PLC wiring and user satisfaction, as illustrated in Figure 2. The pre-test was conducted to ensure that both the experimental and control groups had a similar understanding of electrical and PLC wiring before the study was carried out. The post-test was conducted to compare the performance of students who used the game app outside the laboratory with those who did not, in terms of their wiring skills. Additionally, to assess user satisfaction with the app, the experimental group was requested to fill out a satisfaction questionnaire. Detailed information about the experiment is provided in the following subsections:

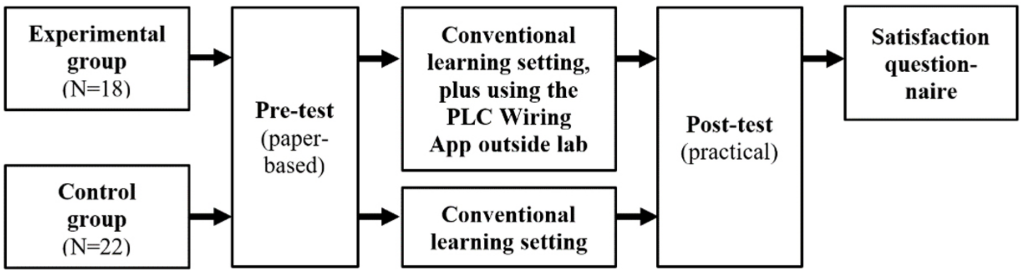

Fig. 2. Diagram of the experimental design

4.1 Participants

In this experiment, a total of 40 participants were involved. All of them were fourth-year undergraduate students majoring in mechanical technology at a public university in Thailand. None of these participants had previously taken any courses related to basic PLCs. The same instructor teaches the Automation course, which covers fundamental PLCs, every semester—the only subject within the curriculum that addresses this topic. Since the number of students per semester was relatively small, averaging around 20 students, we selected 22 students who enrolled in the course during Semester 1/2022 to serve as the control group. The experimental group consisted of 18 students who enrolled in the course in Semester 2/2022 and utilized smartphones or tablets with Android 7.0 or higher.

4.2 Procedure

Before commencing basic PLC instruction in the Automation course, both the control group and the experimental group underwent a paper-based pre-test on electrical fundamentals and PLC wiring. Each sample group was allotted a 20-minute time frame for this pre-test. Following that, the lecturer proceeded to teach the theoretical aspects of PLCs, wiring techniques, and practical exercises, as in previous semesters. This teaching phase lasted for a total of two weeks, with six hours per week. Due to the limited availability of PLC trainers, each practical wiring session required grouping approximately 3–5 students per trainer. Once the two-week teaching period was completed, the following week involved conducting a post-test for each sample group. This involved following the provided instructions to wire the PLC within a 30-minute time frame using pre-attached connector cables. The lecturer evaluated the wiring performance of each student.

Regarding the treatment administered to the experimental group, the additional details are as follows: After the pre-test, the experimental group received instructions to download and install the PLC Wiring App on their smartphones or tablets. The lecturer demonstrated how to use the app and allowed the experimental group to explore its features while addressing any questions they had. Furthermore, a mutual understanding and agreement were reached with the experimental group regarding the requirements and conditions for using the PLC Wiring App for additional self-learning and practice outside the laboratory. The experimental group was given the freedom to choose any day and time for app usage, as well as the number of sessions and duration of each session. However, under the specified conditions, they were required to complete all the beginner-level game stages and achieve time records by playing the advanced-level games at least twice for each mode

(NPN and PNP) before taking the post-test in the following two weeks. Each participant was then instructed to capture screenshots of the game records for both modes and submit them to the lecturer for review at least one day before the post-test. This confirmed that the experimental group adhered to the specified conditions. Upon completing the post-test, the experimental group was asked to fill out a satisfaction questionnaire about the PLC Wiring App.

4.3 Data collection tools

Electrical and PLC wiring basics test. The electrical and PLC wiring basics test consisted of 20 multiple-choice questions, each with four options, of which only one was correct. The first set of 10 questions focused on fundamental electrical wiring concepts relevant to PLC wiring, while the subsequent set of 10 questions specifically addressed essential aspects of basic PLC wiring. To ensure the content validity of the questions, three out of five experts, each with a minimum of five years of experience in basic PLC teaching, thoroughly examined the test. The indices of IOC ranged from 0.67 to 1.00, indicating that all 20 questions were considered suitable.

Performance evaluation form for PLC wiring. The performance evaluation form for PLC wiring was collaboratively developed and reviewed by the same three experts who also reviewed the electrical and PLC wiring basics tests. A scoring rubric was utilized, comprising two assessment criteria and a six-point scale ranging from 0 (unavailable) to 5 (perfect). The first criterion, functionality and compliance, assessed students' ability to correctly connect devices and use the appropriate wire colors. The scoring scale, with six levels arranged in descending order, categorizes predefined ranges of increased incorrect wire connections or improper color usage. This criterion has a weight value of 6, contributing to a maximum score of 30 points. The second criterion, safety and neatness, had a maximum weight of 10 points. The considerations for conducting these checks were specified in five items, each addressing different types of mistakes. This criterion was also rated on a six-point scale in descending order, ranging from no errors detected to all five items found.

Satisfaction questionnaire for the PLC Wiring App. The satisfaction questionnaire for the PLC Wiring App used a five-point Likert scale, ranging from 1 (strongly disagree) to 5 (strongly agree). Initially, a set of 14 items was developed based on the game user experience satisfaction scale (GUESS) [33], which is widely used to assess player satisfaction in educational digital games [34], [35]. The questionnaire was then reviewed by three experts in educational technology to ensure its validity. Three more items were included following their suggestions, resulting in a 17-item questionnaire. The index of IOC for each item reached a value of 1.00, indicating that all items were suitable for use.

4.4 Data analysis

The pre-test was conducted on the experimental group and the control group to ensure that both groups had an equal foundation in electrical and PLC wiring. Since the data obtained from each group followed an approximately normal distribution, the independent sample t-test was used with a significance level of 0.05. The average pre-test scores for the experimental group and control group were 6.61 (SD = 1.91) and 6.45 (SD = 1.85), respectively. The t-test result ($t = 0.263$, $p = 0.794 > 0.05$) indicates that there is no significant difference between the groups. This suggests that both groups had an equal understanding of electrical and PLC wiring before the implementation.

Since both groups possessed comparable prior knowledge before the study, and given the non-normal distribution of data from the post-test in the experimental group, we employed both parametric and non-parametric methods for data analysis. This approach ensures a more robust and clearer conclusion regarding the impact of the developed game app on wiring performance between the two groups. Specifically, we utilized the independent samples t-test and the Mann-Whitney U test, with a significance level of 0.05. In terms of user satisfaction, we analyzed and presented the evaluation results from the experimental group using the mean and standard deviation.

5 RESULTS AND DISCUSSION

5.1 Developed game application

Fig. 3. Example screenshots of the PLC Wiring App

Figure 3 presents screenshots of the PLC Wiring App, which was developed based on the game design described in Section 3 and revised according to the comments and suggestions of the expert groups. Figure 3a and b show the main menu and the NPN Beginner game menu, respectively. When the three-dot circular button on each stage in Figure 3b is pressed, the content of that stage will pop up, allowing players to study it before entering that stage. Figure 3c presents an example of Stage 4 of the game. When the info button for each device is pressed, information about that device will pop up, as depicted in Figure 3d. Figure 3e showcases an example of an advanced-level game. Figure 3f shows examples of assistance and various suggestions that appear when the blue Help button in the top-left corner is pressed.

The PLC Wiring App's final version was approved after incorporating feedback from expert groups. The comprehensive evaluation results for each aspect, such as content, design, operation, and usefulness, are presented in Table 2. The average evaluation score for the overall assessment was 4.43 (SD = 0.33). This indicates that, according to the opinions of the expert groups, the developed game app was highly suitable for students to independently practice PLC wiring outside the laboratory.

Table 2. Expert evaluation results for the PLC Wiring App

No.	Evaluation Aspect	Mean	SD	Interpretation
1.	Content	4.60	0.30	Highly suitable
2.	Design	4.02	0.45	Suitable
3.	Operation	4.52	0.34	Highly suitable
4.	Usefulness	4.56	0.23	Highly suitable
	Overall	4.43	0.33	Highly suitable

Notes: Interpretation: highly unsuitable (1.00–1.80), unsuitable (1.81–2.60), moderately suitable (2.61–3.40), suitable (3.41–4.20), highly suitable (4.21–5.00).

5.2 Effect on student performance and user satisfaction

As the post-test scores of the experimental group deviated from a normal distribution, we employed both parametric and non-parametric methods to assess how the use of the developed game app influenced the cognitive performance of the experimental group compared to the control group. First, the independent sample t-test was conducted at a significance level of 0.05. As shown in Table 3, the t-test result ($t = 2.738$, $p = 0.009 < 0.05$) indicates a significant difference between the groups. The average post-test score for the experimental group was 33.89 (SD = 6.91), which was higher than that of the control group, with an average score of 27.45 (SD = 7.76).

Table 3. The results of the independent t-test for the post-test scores

Group	N	Mean	SD	t	p
Experimental	18	33.89	6.91	2.738	0.009
Control	22	27.45	7.76		

Next, the Mann-Whitney U test was conducted at a significance level of 0.05. As indicated in Table 4, the z-test result ($z = -2.578$, $p = 0.01 < 0.05$) demonstrates a significant difference between the two groups. Notably, the average rank of the post-test scores for the experimental group was 25.72, surpassing that of the control group, which had an average rank of 16.23. The consistent agreement between the results obtained from both parametric and non-parametric methods leads us to conclude that additional practice with the developed game app outside the laboratory resulted in improved performance in PLC wiring compared to students who did not have access to the app.

Table 4. The results of the Mann-Whitney U test for the post-test scores

Group	N	Mean Rank	Sum of Ranks	z	p
Experimental	18	25.72	463.00	−2.578	0.010
Control	22	16.23	357.00		

Table 5 presents the results of the data analysis regarding user satisfaction, including self-reported feedback on users' perceptions of the PLC Wiring App. The average scores for each questionnaire item in the experimental group ranged from 3.72 to 4.56, all exceeding the value of 3.40. This indicates that students had a positive perception of their experience, as reflected in their responses to each question. Furthermore, the analysis of the overall experience revealed positive feedback, with an average satisfaction score of 4.25 (SD = 0.71).

Table 5. User satisfaction results of the PLC Wiring App

Item	Mean	SD
1. Learning how to play the game is straightforward.	4.28	0.46
2. It is clear how to accomplish goals/objectives in the game.	4.50	0.51
3. The game's interface is user friendly.	4.28	0.67
4. The in-game information is unambiguous.	3.94	0.64
5. The game's graphics fit the game style.	4.17	0.92
6. The game's sound effects fit the game style.	4.06	1.00
7. Losing track of time occurs sometimes while playing the game.	4.06	0.94
8. The game keeps me playing longer than I initially intended.	3.72	0.67
9. I enjoy playing the game while getting practice at the same time.	4.56	0.70
10. I will certainly recommend the game to other students.	4.50	0.51
11. I feel successful when I pass each stage/level of the game.	4.50	0.62
12. I want to perform as well as I can while playing the game.	4.06	0.80
13. I feel continually encouraged to play the game in order to advance to the next stage/level.	3.94	0.94
14. My knowledge and abilities regarding PLC wiring improve through the stages/levels of the game.	4.50	0.62
15. I feel more confident in performing PLC wiring after completing all stages/levels of the game.	4.39	0.70
16. The game helps facilitate faster and more efficient learning in PLC wiring.	4.28	0.75
17. The game is suitable for additional PLC wiring training outside the laboratory.	4.56	0.62
Overall	4.25	0.71

Notes: Interpretation: strongly disagree (1.00–1.80), disagree (1.81–2.60), moderately agree (2.61–3.40), agree (3.41–4.20), strongly agree (4.21–5.00).

According to the students' evaluations, it can be concluded that the developed game app provided a satisfactory user experience. Items 1 to 4 in Table 5 highlight the acknowledged usability, as highlighted by. This recognition is attributed to the well-structured interconnected components, the simplified user interface, the provision of immediate feedback, and the use of straightforward and uncomplicated language. The visual and audio aspects were deemed suitable in Items 5 and 6. Clear and appropriate goal setting, coupled with level/staged progression and unlocking mechanisms signifying learning progress, as well as the incorporation of time and leaderboards to highlight the fastest completion times for advanced-level games, all fostered a sense of achievement and kept students engaged. This is evidenced by Items 11 to 13 and Items 7 to 8, respectively. Furthermore, the challenges were designed to be suitable and varied for both novice and advanced players, in accordance with [36] and [37], which suggest that adjusting challenges based on learners' growing knowledge and abilities promotes student engagement. In addition to the points mentioned earlier, students' favorable perception of the app's utility and enjoyment, as indicated by Items 14 to 17 and Item 9, respectively, significantly influenced their inclination to recommend the app to their friends, as expressed in Item 10.

The study's findings indicate that the students' favorable perception of the app was strengthened by their performance. It was found that extra practice with this gaming app led to improved performance in PLC wiring, compared to students who did not use the app. This conclusion is drawn from the analysis of post-test scores of the sample group, which yielded consistent results in both parametric and non-parametric methods, as shown in Tables 3 and 4, respectively. One contributing factor to this positive outcome is that the app allows for learning and practice at any time and place, accommodating students' convenience and pace. This is consistent with previous studies that utilized various technologies, such as virtual reality [38], computer simulation [39], and others, to develop tools that offer learning flexibility and improve student learning. Additionally, the app's design was intended to engage and entertain students, thereby leading to more effective learning outcomes. This is consistent with [40], where game design related to solar systems was implemented with appropriate game mechanics and elements to promote student engagement and enjoyment, leading to improved learning outcomes.

However, it is worth noting that our study reveals a weakness related to the representation of devices within the game. They are depicted solely by names and symbols, rather than lifelike or 3D images. Some students may not be familiar with the appearance of these devices when they use them in real-life situations. Even though 2D photographs of the devices are available in the information section of each device, students must click the information button for each device every time to access them. However, this game app can still enhance most students' confidence in performing PLC wiring after completing the game, as shown by item 15 in Table 5.

6 CONCLUSION

In this paper, we aim to introduce an educational game app designed and developed to enable students to practice basic PLC wiring on their smartphones or tablets without any time or location constraints. It received approval from experts, with overall assessments indicating its high suitability for use. Subsequently, we conducted an experiment with a sample group of 40 students, including 22 in the control group and 18 in the experimental group. The experimental group was given access to the game app for extra practice outside the laboratory. The study found that the additional practice with the developed gaming app led to improved performance in PLC wiring compared to students who did not have access to the app. Furthermore, the feedback from students about their experience using the game app indicated the highest level of satisfaction. Therefore, we consider this game app to be an effective learning tool capable of enhancing student performance and facilitating a more engaging learning experience in basic PLC wiring.

It is hoped that this study will serve as a reference and encourage the development of more educational game apps to be used as complementary or supplementary learning tools in PLC wiring training. These apps can start at the basic level and progress to the advanced level. This will enable students to learn and practice more while enjoying the gaming experience, especially considering their limited access to time and equipment in the laboratory. It will support them in effectively enhancing their learning and aligning with their individual learning pace. Furthermore, it can help create a safer learning environment for practicing PLC wiring, reducing potential risks to students and minimizing the possibility of damage to lab equipment. Finally, for educational institutions that do not have appropriate lab equipment for PLC wiring training, we highly recommend utilizing educational game apps as a learning tool to offer students a more engaging learning experience in PLC wiring.

7 LIMITATIONS AND FUTURE STUDIES

In this study, the game engine used was Unity, which allows users to develop game apps for both iOS and Android platforms. However, due to budget constraints and the unavailability of iOS devices for app development, students in the experimental group were limited to using smartphones or tablets running on the Android platform only. Additionally, the in-game PLC device was limited to a single model, the Mitsubishi FX5U-32MR/ES. Therefore, it is recommended to develop additional options that enable a wider range of PLC devices to be selected in future studies. Moreover, it is recommended to conduct research on advanced-level PLC wiring content. Furthermore, it is recommended to investigate research pertaining to the utilization of this technology in situations where there is a lack of available equipment for conducting PLC wiring experiments in laboratories.

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