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PAPER

Development of Innovative Mobile QR-EFI Simulator in Problem-Based Teaching Factory (PBTF) Model to Enhance Students' 4C Skills

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ABSTRACT

This study addresses the urgent need to bridge the competency gap between vocational education graduates and the rapidly evolving demands of the modern automotive industry, particularly in the increasingly complex electronic fuel injection (EFI) systems. Conventional learning approaches have proven insufficient in equipping students with the necessary technical and non-technical skills to adapt to current technologies. Therefore, this study aims to develop and validate a mobile-based EFI simulator integrated with QR code technology, enabling interactive visualization of the components, data flow, operational processes, and diagnostic procedures of the EFI system in an easily understandable manner. The simulator's effectiveness is further evaluated through its integration within the Problem-Based Teaching Factory (PBTF) model to enhance students' 4C skills: collaboration, communication, creativity, and critical thinking. Employing a Research and Development (R&D) approach with the 4-D model (Define, Design, Develop, Disseminate), the study involved 50 Automotive Engineering students at FT-UNP, divided into experimental and control groups. Validity analysis using SEM-PLS confirmed high validity of the simulator, especially in visualization aspects, while effectiveness testing showed that the experimental group using the simulator scored significantly higher in 4C skills than the control group. These results confirm that integrating the Mobile QR-EFI Simulator within the PBTF model significantly improves students' critical and creative skills, bridges the gap between theory and practice in vocational automotive education, and meets the demand for interactive learning tools aligned with modern industry developments.

KEYWORDS

mobile QR-EFI simulator, problem-based teaching factory (PBTF), 4C skills, vocational education, electronic fuel injection system

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1 INTRODUCTION

The digital era requires education to develop the 4C skills critical thinking, communication, collaboration, and creativity as essential for navigating 21st-century complexities. Critical thinking helps students evaluate information and make evidence-based decisions amid unverified digital data [1–3]. While effective communication is vital for clear idea exchange on digital platforms and global learning. In vocational education, critical thinking and communication are crucial due to industrial automation's demand for advanced cognitive and interpersonal skills beyond AI capabilities [4–5].

Collaboration and creativity are essential for preparing students to tackle future challenges, where multidisciplinary teamwork drives innovation and problem-solving [6]. Creativity thrives in supportive learning environments, and integrating digital technology, especially e-learning, significantly enhances 4C skills, promoting holistic development for a complex, dynamic workforce [7–9].

The Problem-Based Teaching Factory (PBTF) model bridges theory and practice by integrating complex problem-solving with real production experience. Through five steps problem identification, solution planning, implementation, quality control, and reflection PBTF develops the 4C skills (critical thinking, communication, collaboration, and creativity) and prepares learners to adapt to technological changes and labor market demands in the digital era [10]. The PBTF model syntax illustration is depicted in Figure 1.

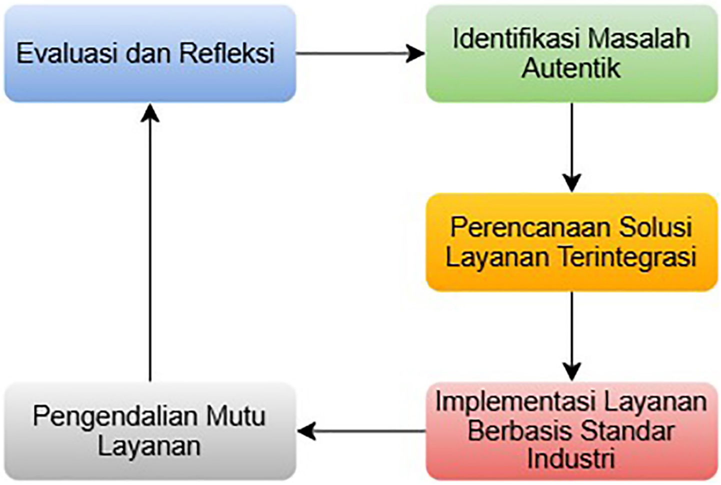

Fig. 1. PBTF model syntax illustration

The competency gap between vocational graduates and industry needs is a major challenge in Indonesia, especially in mastering technical skills and soft skills relevant to Industry 4.0. [11–12]. The rapid digital transformation is not matched by adaptive curricula and teaching methods, and weak communication between education and industry exacerbates this problem. Recent evaluations emphasize the importance of strengthening 4C skills (critical thinking, communication, collaboration, and creativity) to address these challenges, while the role of the Special Employment Exchange as a link between graduates and industry remains suboptimal [13–16].

Researchers note that EFI learning at FT-UNP faces challenges from system complexity, limited facilities, and costly equipment, making conventional methods ineffective. Rapid EFI advances hinder material updates, causing competency gaps.

Developing innovative models like the PBTF integrated with the mobile QR-EFI Simulator effectively enhances students' 4C skills.

Lecture-based EFI learning leads to passive students with weak 4C skills and poor theory-to-practice application. The system's complexity demands affordable, user-friendly interactive tools that visualize processes, simulate operations, and provide real-time feedback. Augmented reality technology is a key solution supporting Industry 4.0-aligned learning [17–18].

The impact of this issue is strongly felt in vocational education. Despite high mobile device penetration, vocational automotive education underutilizes them, lacking dedicated mobile EFI learning apps that limit student access to simulations anytime, anywhere. Meanwhile, technology-based learning and the PBTF model effectively boost student interest and achievement through digital modules [19–20].

This study aims to design a mobile-based EFI simulator integrated with QR code technology, allowing students to interact with a virtual EFI system on their devices. The simulator visually presents system components, data flows, processes, and diagnostics through an intuitive interface, simulating various operational and failure scenarios. Leveraging mobile technology in learning has been shown to significantly enhance student outcomes and skills development, as demonstrated by studies on the Rifdarmon-based e-learning model [8, 21]. The mobile QR-EFI simulator is constructed in Figure 2.

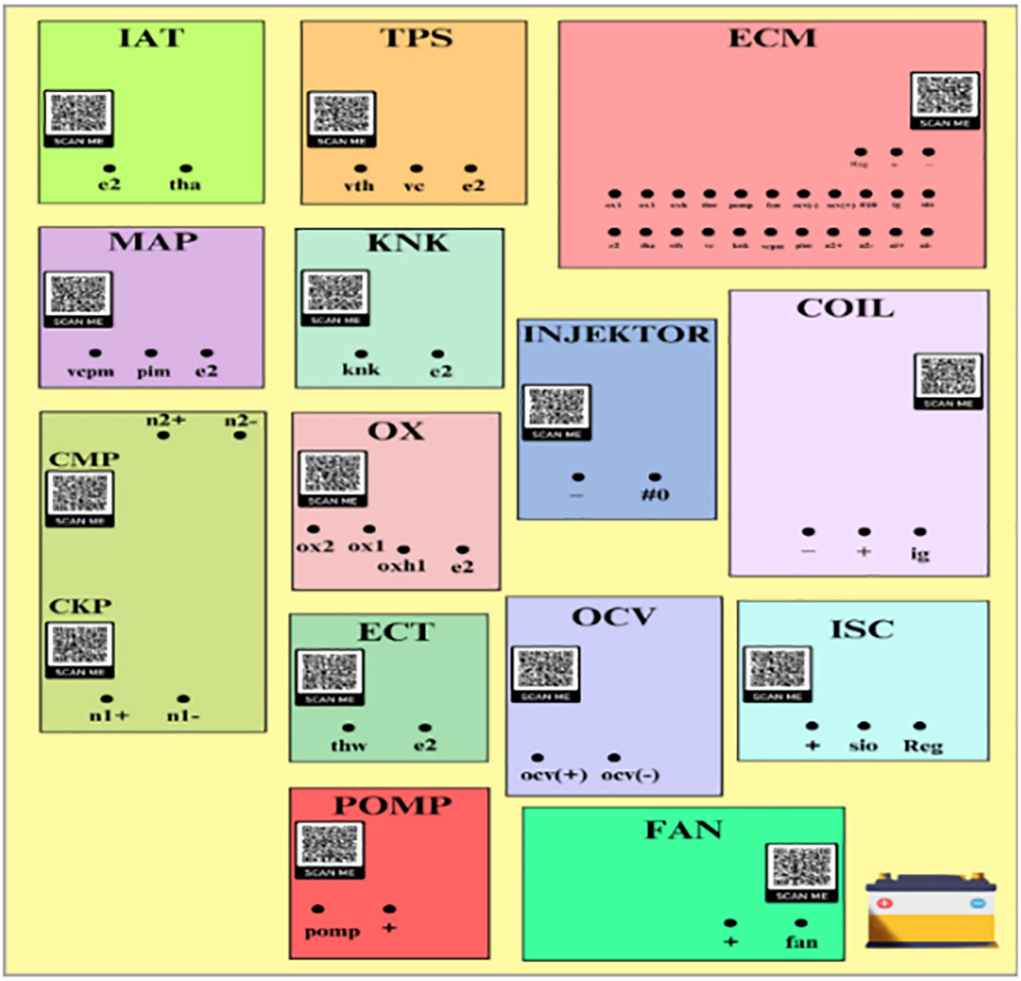

Fig. 2. Mobile QR-EFI simulator construction

2 LITERATURE REVIEW

The development of the Mobile QR-EFI simulator integrated with the PBTF model is based on the study by Supriyanto and Rohmantoro, who developed Android-based EFI learning media to enhance students' understanding through interactive visualization. This finding is supported by Maksum et al. [20], who demonstrated the effectiveness of the PBTF model with Teaching Factory (TEFA-T) in improving student learning achievement through the use of digital learning modules. This study reinforces the argument that the PBTF model can bridge the gap between theory and practice in vocational education, as the model "operationalizes the development of 4C skills through five systematic syntaxes" that combine complex problem-solving with real production experience.

The integration of mobile technology in learning has been proven to improve student outcomes and engagement, as demonstrated by Rifdarmon et al. [21] Their study confirms that the use of mobile devices can significantly enhance learning effectiveness, supporting the statement that "mobile device penetration is very high among students," but its potential is "not yet optimized to create richer and more contextual learning experiences." In the field of augmented reality, Arpan et al. [23] developed a mobile-based augmented reality learning solution to enhance skill development, reinforcing the claim that "augmented reality technology is an important complement in learning to face the Industry 4.0 Revolution," with the ability to visualize abstract concepts into virtual representations that are easier for students to understand.

Sumarsono and Sugiyanto developed an Android-based learning media for transistor practicum that effectively enhances the understanding of electronics, supporting the importance of developing the Mobile QR-EFI simulator, which "dynamically visualizes the working process of the EFI system and simulates various operational conditions and system failures," as explained by Khairani and Maksum [24]. They also made an important contribution by developing Android-based learning media for the course on simulation and digital communication. Their research confirms that the integration of mobile technology in learning can enhance student engagement and motivation in the learning process, aligning with the objectives of developing the Mobile QR-EFI simulator.

Salim et al. [25] used the UML 2.5 approach to design an Android-based mathematics learning application, providing a systematic framework relevant to developing a mobile-based EFI simulator. This approach supports the study objective of "designing and developing a mobile-based EFI simulator integrated with QR code technology" by enabling structured design for interactive features and integration of physical and digital components. Indah et al. [26] adapted a similar methodology for automotive engineering education, demonstrating the effectiveness of Android-based learning media in improving student outcomes in ICT at the high school level. These findings reinforce the argument that mobile technology has significant potential to enhance education quality across levels, including vocational automotive engineering, by offering more interactive, flexible, and contextual learning access.

Apriliana and Wulandari [27] developed an Android-based science app on the Solar System, demonstrating mobile apps' flexibility to visualize complex concepts interactively, paralleling EFI system challenges in automotive education. This supports using similar technologies for more tangible, contextual visualizations [28]. The development of an augmented reality app for computer networks enhances understanding of complex technical concepts, aligning with the introduction's statement that "there is an urgent need for interactive learning tools capable of visualizing the working processes of complex systems." Efendi et al. [29] found that immersive, mobile-based augmented reality can bridge the Industry 4.0 skills gap in vocational education, reinforcing the argument that "the gap between the competencies of vocational education graduates and industry needs is a significant challenge in the Indonesian education system." Integrating augmented reality into learning offers an effective solution to prepare students for modern industry demands.

Based on the analysis, previous research reveals gaps in developing the Mobile QR-EFI simulator with the PBTF model to enhance 4C skills: limited exploration of QR code integration linking physical and digital components; lack of specific studies on PBTF's effectiveness for EFI-related 4C skills; scarce use of augmented reality for dynamic EFI visualization; insufficient focus on diagnostics and problem-solving in mobile AR learning; absence of comprehensive impact assessments of mobile simulators integrated with PBTF on 4C skills; and no adaptation of UML 2.5 methodology for designing EFI simulators combining QR technology with physical-digital integration.

This study innovates vocational automotive education by developing a mobile QR-EFI simulator integrated with the PBTF model. The simulator links physical components to interactive digital simulations via QR codes, enabling authentic, contextual learning. It simulates normal and failure EFI operations to enhance students' diagnostic and problem-solving skills in a safe virtual setting. Integrated throughout PBTF stages, it optimizes 4C skill development. Evaluations confirm its significant impact on 4C skills, supported by dynamic mobile and augmented reality visualizations. The design follows UML 2.5 methodology, offering a holistic paradigm aligned with modern industry demands and digital vocational education to better prepare students for the workforce.

The urgency of this study addresses the competency gap between vocational graduates and modern automotive industry demands, especially the complex EFI systems. Conventional methods fall short in developing technical and 4C skills. Thus, a Mobile QR-EFI Simulator integrated with the PBTF model was developed to provide interactive EFI visualization and enhance students' collaboration, communication, creativity, and critical thinking. This study evaluates the simulator's design validity and effectiveness in vocational automotive education.

This study is significant in three key aspects: first, it advances educational technology by developing the Mobile QR-EFI Simulator, which integrates mobile technology, QR codes, and virtual simulation to create an interactive learning experience. Second, it enhances EFI system learning by intuitively visualizing complex processes, making difficult concepts easier to understand. Third, it strengthens students' 4C skills through the simulator's integration with the PBTF model, preparing them for modern automotive industry challenges with both technical and interpersonal abilities. Additionally, this learning model is adaptable to other engineering fields, broadening its impact on vocational and technical education.

3 RESEARCH METHODS

This study employs a Research & Development (R&D) method using the 4-D model (Define, Design, Develop, Disseminate) involving 50 Automotive Engineering students from FT-UNP, randomly divided into an experimental group (n = 25) using the Mobile QR-EFI Simulator with the PBTF model and a control group (n = 25) using conventional methods. Random class assignment ensures internal validity and minimizes bias. Two main instruments were used: simulator validation covering content, functionality, interface, user experience, PBTF integration, and visualization; and assessment of 4C skills (critical thinking, communication, collaboration, and creativity), both validated by experts before implementation. Data were collected through validation questionnaires and structured observations during learning. Analysis was conducted in two stages: first, instrument validity was analyzed using SEM-PLS with SmartPLS 4, including convergent validity, discriminant validity, reliability, and structural model evaluation; second, simulator effectiveness was tested through normality and homogeneity prerequisite tests, followed by paired-sample t-tests to compare the development of 4C skills between the experimental and control groups.

4 RESULT AND DISCUSSION

4.1 Result

This study validates and assesses the effectiveness of the Mobile QR-EFI Simulator within the PBTF model to enhance students' 4C skills. Validation used SEM-PLS analysis via SmartPLS4 on instruments measuring functionality, PBTF integration, material suitability, visualization quality, user experience, and interface. The results of the Mobile QR-EFI Simulator validation can be seen in Figure 3 and Table 1.

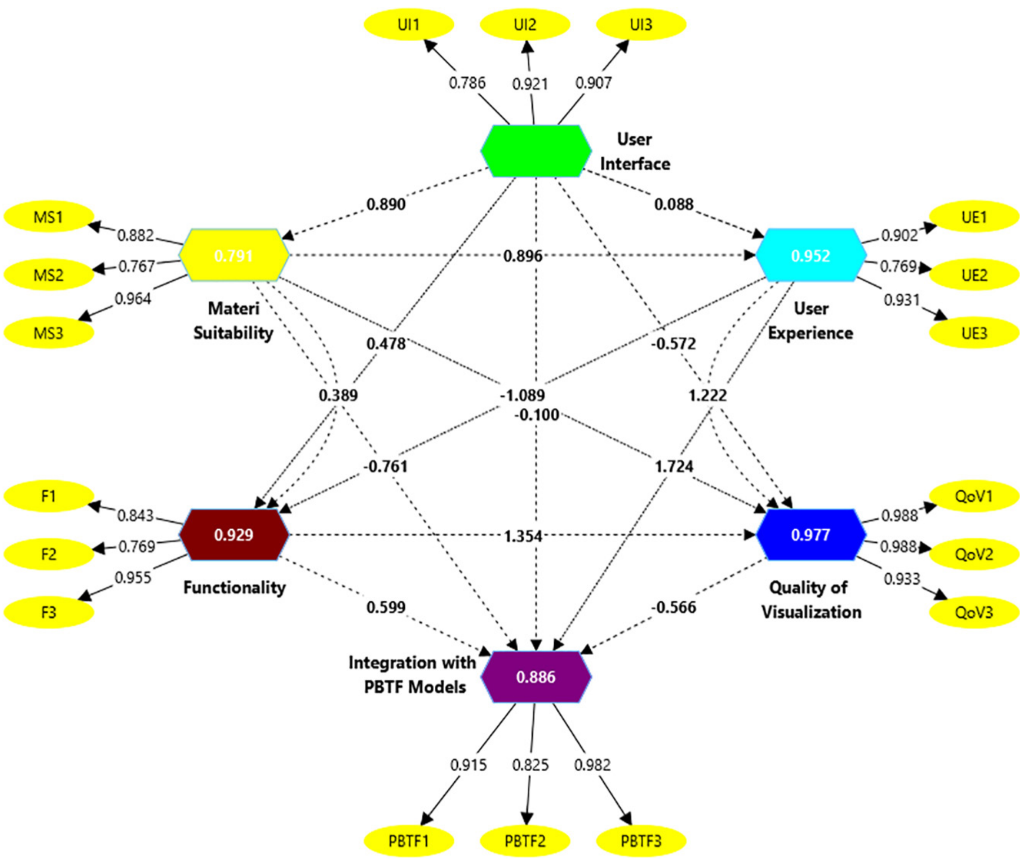

Fig. 3. Grapichal output of SEM-PLS of mobile QR-EFI simulator

Table 1. Results of mobile QR-EFI simulator validity data

Aspect Assessment	Composite Reliability		Cronbach's Alpha	AVE
	(rho_a)	(rho_c)		
Functionality	0.845	0.893	0.818	0.738
Integration with PBTF Models	0.922	0.935	0.895	0.827
Material Suitability	0.887	0.907	0.846	0.765
Quality of Visualization	0.979	0.980	0.969	0.941
User Experience	0.870	0.903	0.838	0.757
User Interface	0.876	0.906	0.845	0.763

Based on the analysis results shown in Figure 3 and Table 1, all assessment aspects of the Mobile QR-EFI Simulator demonstrated good validity. The functionality aspect showed a Cronbach's Alpha of 0.845, a Composite Reliability of 0.893, a rho_a of 0.818, and an AVE of 0.738. Integration with PBTF models recorded the highest values with a Cronbach's Alpha of 0.922, Composite Reliability of 0.935, a rho_a of 0.895, and AVE of 0.827. Material Suitability obtained a Cronbach's Alpha of 0.887, Composite Reliability of 0.907, rho_a of 0.846, and an AVE of 0.765. Quality of Visualization stood out with a Cronbach's Alpha of 0.979, Composite Reliability of 0.980, rho_a of 0.969, and AVE of 0.941. User Experience had a Cronbach's Alpha of 0.870, Composite Reliability of 0.903, rho_a of 0.838, and AVE of 0.757, while User Interface achieved a Cronbach's Alpha of 0.876, Composite Reliability of 0.906, rho_a of 0.845, and AVE of 0.763. Furthermore, the 4C skills assessment instrument, which includes Collaboration, Communication, Creativity, and Critical Thinking, was validated using the SEM-PLS technique with SmartPLS 4, demonstrating adequate reliability and validity for evaluating student skills. The results of the Mobile QR-EFI Simulator validation can be seen in Figure 4 and Table 2.

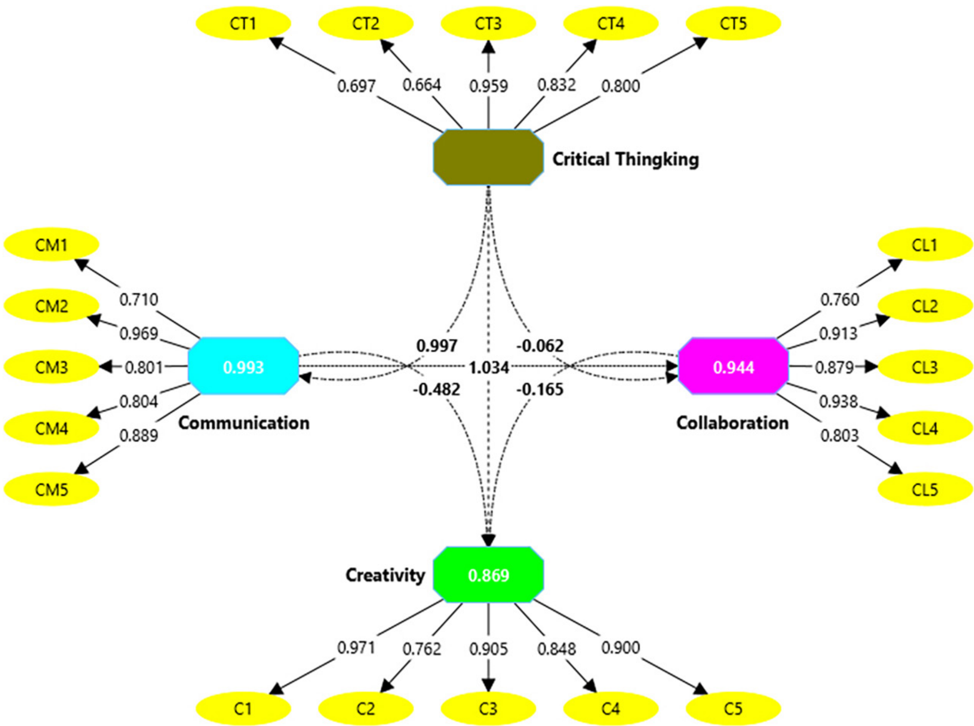

Fig. 4. Graphical output of SEM-PLS of assessment instrument 4C

Table 2. Results of validity data of assessment instrument 4C

Aspect Assessment	Composite Reliability		Cronbach's Alpha	AVE
	(rho_a)	(rho_c)		
Collaboration	0.933	0.934	0.912	0.742
Communication	0.911	0.922	0.892	0.705
Creativity	0.943	0.944	0.926	0.774
Critical Thinking	0.871	0.896	0.850	0.636

Based on the validation results displayed by Figure 4 and Table 2, it can be seen that the Collaboration aspect has a Cronbach's Alpha of 0.933, a Composite Reliability of 0.934, a rho_a of 0.912, and an AVE of 0.742. The communication aspect obtained a Cronbach's Alpha of 0.911, Composite Reliability of 0.922, a rho_a of 0.892, and an AVE of 0.705. Creativity recorded the highest values with a Cronbach's Alpha of 0.943, Composite Reliability of 0.944, rho_a of 0.926, and AVE of 0.774. The final aspect, Critical Thinking, has a Cronbach's Alpha of 0.871, a Composite Reliability of 0.896, a rho_a of 0.850, and an AVE of 0.636. Overall, validity results for the Mobile QR-EFI Simulator and 4C skills assessment instruments show satisfactory values, confirming their reliability to measure the PBTF model's effectiveness. Following validation, data were collected on the simulator's impact within the PBTF model on students' 4C skill development; it can be described as shown in Table 3.

Table 3. Frequency distribution of student 4C skills data

Descriptive Statistics					
	N	Minimum	Maximum	Mean	Std. Deviation
Control Class	25	64	82	75.64	4.462
Experiment Class	25	80	95	86.40	4.311

The analysis of the frequency distribution of students' 4C skills shows a significant difference between the control and experimental classes. The control class (n = 25) had a minimum score of 64, a maximum of 82, an average of 75.64, and a standard deviation of 4.462. In contrast, The experimental class (n = 25) scored higher, with a minimum of 80, a maximum of 95, an average of 86.40, and an SD of 4.311 – 10.76 points above the control group average. The experimental group's minimum exceeding the control's average underscores the Mobile QR-EFI Simulator integrated with PBTF's effectiveness in enhancing students' 4C skills. After obtaining the descriptive data, a normality test was conducted, with the results shown in Table 4.

Table 4. Normality test results

Tests of Normality						
	Kolmogorov-Smirnova			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
Control Class	.142	25	.200*	.947	25	.216
Experiment Class	.173	25	.053	.910	25	.031

Notes: * This is a lower bound of the true significance. a. Lilliefors Significance Correction.

Based on Table 4, normality tests were conducted using the Kolmogorov-Smirnov and Shapiro-Wilk methods. For the control group, the Kolmogorov-Smirnov statistic was 0.142 with df 25 and a significance value of 0.200* (the lower bound of significance), while the Shapiro-Wilk statistic was 0.947 with a significance of 0.216. Both results indicate a normal distribution since their significance values are greater than 0.05. Meanwhile, for the experimental group, the Kolmogorov-Smirnov test indicated normality with a significance of 0.053, slightly above 0.05, but the Shapiro-Wilk test showed non-normality with a significance of 0.031, below the 0.05 threshold. Thus, the control group data can be considered normally distributed, whereas the experimental group data shows mixed results depending on the test used. After the normality test results were obtained, a homogeneity test was conducted, with the results shown in Table 5.

Table 5. Homogenity test result

Tests of Homogeneity of Variances					
		Levene Statistic	df1	df2	Sig.
4C Skills Score	Based on Mean	.018	1	48	.894
	Based on Median	.010	1	48	.921
	Based on Median and with adjusted df	.010	1	47.751	.921
	Based on trimmed mean	.006	1	48	.940

Based on Table 5, the homogeneity test using Levene's method was performed with four different approaches. The "Based on Mean" approach yielded a test statistic of 0.018 (df1 = 1, df2 = 48) with a significance value of 0.894. The "Based on Median" approach showed a test statistic of 0.010 (df1 = 1, df2 = 48) and significance of 0.921. Similarly, the "Based on Median with adjusted df" approach reported a test statistic of 0.010 (df1 = 1, df2 = 47.751) with a significance of 0.921. The "Based on Trimmed Mean" approach resulted in a test statistic of 0.006 (df1 = 1, df2 = 48) and significance of 0.940. All significance values exceed 0.05, indicating that the variances of 4C skills scores between the control and experimental groups are homogeneous. Therefore, the observed differences in mean scores are not due to variance differences, justifying the use of a paired samples T-test for further analysis, with the results shown in Table 6 below.

Table 6. Paired samples T-Test result

Paired Samples Test										
		Paired Differences					t	df	Significance	
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference				One-Sided p	Two-Sided p
					Lower	Upper				
Pair 1	Control Class – Experiment Class	–10.760	5.652	1.130	–13.093	–8.427	–9.520	24	<.001	<.001

Based on Table 6, the paired samples T-test results show a mean difference of –10.760 between the experimental and control groups, with a standard deviation of

5.652 and a standard error of the mean of 1.130. The negative value indicates that the experimental group scored higher. The 95% confidence interval ranges from –13.093 to –8.427, confirming that the population mean difference lies within this range. The calculated t-value of –9.520 with 24 degrees of freedom indicates a significant difference. The p-value <0.001 is well below $\alpha = 0.05$, making this result highly statistically significant. The results show a significant difference between the 4C skills scores of the control and experimental classes, proving that the use of the Mobile QR-EFI Simulator within the PBTF model effectively enhances students' 4C skills. This finding supports the hypothesis that the implementation of the simulator has a positive impact on the development of students' collaboration, communication, creativity, and critical thinking skills.

4.2 Discussion

The study results show that the Mobile QR-EFI Simulator has high validity based on SEM-PLS analysis. All assessment aspects exceeded minimum thresholds for Cronbach's Alpha, Composite Reliability (rho_c), rho_a, and Average Variance Extracted (AVE), confirming strong validity and reliability. The Quality of Visualization aspect scored highest, with a Cronbach's Alpha of 0.979, Composite Reliability of 0.980, rho_a of 0.969, and AVE of 0.941, indicating excellent interactive visualization of EFI components, data flows, processes, and diagnostics. This confirms the simulator effectively achieves the study goal of providing a dynamic and clear visualization of the EFI system's working processes.

The integration with the PBTF model aspect also showed high validity with a Cronbach's Alpha of 0.922, indicating that the simulator is well integrated into the PBTF learning model. The validation results of the 4C skills assessment instrument also demonstrated high validity and reliability. The creativity aspect recorded the highest values with a Cronbach's alpha of 0.943, a Composite Reliability of 0.944, a rho_a of 0.926, and an AVE of 0.774, followed by collaboration (Cronbach's alpha 0.933), communication (Cronbach's alpha 0.911), and critical thinking (Cronbach's alpha 0.871). This indicates that the study instruments have a strong capability to validly and reliably measure students' 4C skills. The results showed a significant difference in 4C skills between the control and experimental classes. The experimental class, using the Mobile QR-EFI Simulator within the PBTF model, achieved a higher average score of 86.40 compared to 75.64 in the control class, a substantial improvement of 10.76 points. The Paired Samples T-Test confirmed this difference as highly significant ($t = –9.520$, $p < 0.001$). Notably, the experimental class's minimum score (80) exceeded the control class average, further confirming the simulator's effectiveness in enhancing collaboration, communication, creativity, and critical thinking. These findings align with the study objectives to evaluate the Mobile QR-EFI Simulator's impact on developing students' 4C skills through PBTF integration.

The study results show a significant difference between the control and experimental groups in students' 4C skills. The experimental group, which used the Mobile QR-EFI Simulator within the PBTF model, performed significantly better than the control group, with an average score of 86.40 compared to 75.64. This mean difference of 10.76 points indicates a substantial improvement in the experimental group. The paired samples T-test results, with a t-value of –9.520 and a significance level less than 0.001 ($p < 0.001$), confirm that this difference is highly statistically significant. These findings prove that the use of the Mobile QR-EFI Simulator integrated into the PBTF model is effective in enhancing students' collaboration, communication, creativity, and critical thinking skills. The minimum score in the experimental group (80) is even higher than the average score of the control group (75.64), further strengthening the evidence of the simulator's effectiveness. These results align with the study objective to evaluate the effectiveness of the Mobile QR-EFI Simulator integrated within the PBTF model in developing students' 4C skills.

This study's findings align with prior research that forms its conceptual basis. The significant improvement in students' 4C skills using the Mobile QR-EFI Simulator confirms Supriyanto and Rohmantoro's results [22] which showed that Android-based EFI learning media enhances understanding of complex EFI concepts. Interactive mobile visualization facilitates easier comprehension of EFI components and principles compared to conventional methods. Additionally, the effectiveness of combining the PBTF model with the mobile simulator supports Maksum et al. [20] findings that PBTF with Teaching Factory (TEFA-T) improves academic achievement through digital learning modules. The Mobile QR-EFI Simulator effectively operationalizes 4C skill development by integrating complex problem-solving with real production experience in a systematic way.

The high validation scores for quality of visualization align with Arpan et al. [23] who found that augmented reality effectively visualizes abstract concepts for easier student understanding. Strong validity in user experience and interface supports Rifdarmon et al. [21] findings that mobile devices enhance engagement and learning effectiveness. The improvement in 4C skills with the Mobile QR-EFI Simulator also confirms Khairani and Maksum's results on mobile technology boosting student motivation. Additionally, the creativity aspect's top validity aligns with Efendi et al. [29] showing immersive mobile AR learning bridges the Industry 4.0 skills gap in vocational education.

The success of developing the Mobile QR-EFI Simulator integrated with QR code technology also reinforces the methodology used by Salim et al. [25] in designing Android-based learning applications using the UML 2.5 approach. The significant improvement in students' 4C skills through the use of this simulator also aligns with the research of Indah et al. [26] which proves the effectiveness of Android-based learning media in improving student learning outcomes. Overall, this study has successfully achieved its objectives in developing a mobile-based EFI simulator integrated with QR code technology that is valid and effective in enhancing students' 4C skills through the PBTF model. The Mobile QR-EFI Simulator successfully visualizes the EFI system's working processes dynamically and simulates various operational conditions and system failures, providing students with a richer and more contextual learning experience. The integration of this simulator within the PBTF model has been proven to bridge the gap between theory and practice in vocational education, as well as prepare students to meet the demands of the modern industry that require collaboration, communication, creativity, and critical thinking skills.

5 CONCLUSION

The Mobile QR-EFI Simulator demonstrated strong validity across all aspects using SEM-PLS analysis. Functionality showed Cronbach's Alpha of 0.845 and a Composite Reliability of 0.893; Integration with PBTF models had 0.922 and 0.935; material suitability reached 0.887 and 0.907; and quality of visualization scored highest with 0.979 and 0.980, confirming effective EFI system visualization. User Experience and User Interface also showed good validity with Alphas of 0.870 and 0.876. All aspects had AVE values above 0.7, indicating strong convergent validity.

The experimental class using the Mobile QR-EFI Simulator scored significantly higher in 4C skills (86.40) than the control class (75.64), with a 10.76-point difference ($t = -9.520$, $p < 0.001$), confirming its effectiveness in enhancing collaboration, communication, creativity, and critical thinking when combined with the PBTF model. This simulator meets the need for interactive tools that visualize complex systems and bridge theory-practice gaps in vocational education for Industry 4.0.

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