

A Chatbot-Based Expert System for Supporting Conceptual Understanding in DC Circuit Analysis: Development and Evaluation in Electrical Engineering Education

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ABSTRACT

This study addresses the limited development of chatbot-based expert systems that integrate rule-based reasoning and conceptual guidance for direct current (DC) circuit analysis learning in electrical engineering education. The study aimed to develop and evaluate a chatbot-based expert system designed to support students' conceptual understanding of DC circuit analysis. A Research and Development (R&D) approach employing the 4D model (Define, Design, Develop, Disseminate) was applied in this study. The effectiveness evaluation used a one-group pretest-posttest design involving 25 undergraduate students from an Electrical Engineering Education program. The developed system was validated by one electrical engineering expert and two educational media experts before implementation. The validation results showed high validity across all evaluated aspects, with Aiken's V values categorized as very valid. The practicality test indicated that the system was highly practical, achieving a mean score of 4.32 out of 5.00 (86.3%). The effectiveness test showed improvement in students' learning outcomes, reflected by a normalized gain (N-gain) score of 0.32 in the moderate category. In addition, the paired sample t-test demonstrated a statistically significant difference between pretest and posttest scores ($p < 0.001$). Although the study was conducted with a limited sample and without a control group, the findings indicate that the chatbot-based expert system showed potential to support students' conceptual understanding and procedural learning in DC circuit analysis. This study contributes to the development of AI-assisted learning media in vocational and engineering education, particularly in supporting interactive and concept-oriented learning environments.

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1. INTRODUCTION

The rapid advancement of digital technology and artificial intelligence (AI) in the era of the Fourth Industrial Revolution and Society 5.0 has significantly transformed educational practices, particularly in higher education and engineering education. The integration of AI technologies into learning environments has encouraged a transition from teacher-centered instruction toward more student-centered and technology-supported learning approaches. In this context, students are expected not only to master theoretical knowledge but also to develop critical thinking skills, problem-solving abilities, self-regulated learning skills, and the capacity to utilize digital technologies effectively in academic and professional contexts. Recent studies have shown that AI-based educational technologies have considerable potential to support personalized learning, improve learner engagement, and provide adaptive learning assistance in higher education environments (Chiu, 2023; Ouyang et al, 2022; Zawacki-Richter et al, 2019).

One form of AI technology that has attracted increasing attention in education is the educational chatbot. Educational chatbots are conversational systems designed to support learning interactions through natural language communication. Previous studies indicate that educational chatbots can function as virtual learning assistants that provide instructional support, facilitate student engagement, encourage self-regulated learning, and offer immediate feedback during learning activities (Okonkwo & Ade-Ibijola, 2021; Smutny & Schreiberova, 2020; Wollny et al., 2021). In addition, systematic review and meta-analysis studies have demonstrated that chatbot technologies generally produce positive effects on learning outcomes and student motivation when integrated appropriately into educational settings (Deng & Yu, 2023; Alemdag, 2025; Laun & Wolff, 2025). The growing development of generative AI technologies has further expanded the potential use of conversational agents in education, particularly in supporting personalized and flexible learning experiences (Kasneci et al., 2023; Tlili et al., 2023).

Within higher education, chatbot-based learning systems have increasingly been explored as tools capable of supporting independent learning and providing learning assistance beyond classroom limitations. Such systems are particularly relevant in online and hybrid learning environments where instructors cannot always provide individualized support to every learner. Educational chatbots have been reported to support interaction, guidance, and learning accessibility while helping students manage learning activities more independently (Kuhail et al., 2022; Guan et al, 2025). Furthermore, AI-supported learning systems are considered capable of promoting student autonomy and self-regulated learning through adaptive feedback and interactive instructional assistance (Deng & Yu, 2023).

In the context of electrical engineering education, one of the essential competencies that students must master is the ability to analyze direct current (DC) electrical circuits. This competency forms the conceptual foundation for more advanced subjects such as alternating current circuits, control systems, power electronics, and electrical machine analysis. Understanding fundamental concepts such as Ohm's law, Kirchhoff's laws, and circuit analysis techniques, including loop and node analysis, is therefore crucial for students before progressing to more advanced engineering topics.

However, previous studies have shown that many students experience conceptual and procedural difficulties in learning electrical circuit analysis. Students frequently encounter misconceptions related to current flow, voltage relationships, and the application of electrical laws in problem-solving situations (Engelhardt & Beichner, 2003). These learning difficulties are associated with the abstract nature of circuit analysis, which requires logical reasoning, deductive thinking, and systematic analytical skills. In many cases, students tend to apply formulas mechanically without fully understanding the conceptual relationships underlying circuit behavior. Consequently, students often struggle to interpret problems, determine appropriate solution procedures, and explain the reasoning behind their answers.

These challenges are further influenced by limitations in classroom learning practices. Conventional instructional approaches in electrical engineering courses are often dominated by theoretical explanations and procedural demonstrations, while opportunities for individualized conceptual guidance and immediate feedback remain limited. Such conditions may hinder students from developing deeper conceptual understanding and systematic reasoning abilities. In fact, effective learning in engineering

education requires not only procedural knowledge but also conceptual understanding supported by guided practice and timely feedback.

Preliminary observations conducted during the 2024/2025 academic year in Basic Electrical Circuit courses at two electrical engineering education programs, hereafter referred to as University A and University B, also revealed similar learning difficulties among students. The preliminary data were obtained from documented course evaluation results and lecturer observations related to students' performance in DC circuit analysis topics. At University A, out of 20 students participating in the course evaluation, only three students achieved a grade of B, while most students obtained a grade of C, and none achieved a grade of A. Similar findings were identified at University B, where out of 25 students, only three students achieved a grade of B+, one student received a grade of E, and the majority obtained a grade of C.

Although a grade of C is administratively categorized as passing, these results indicate that many students had not yet achieved satisfactory conceptual mastery of DC circuit analysis. The similarity of learning outcome patterns across two different institutions suggests that difficulties in understanding electrical circuit analysis remain a substantial challenge in electrical engineering education. These findings indicate the need for learning support systems capable of providing structured conceptual guidance, procedural assistance, and immediate feedback to help students understand reasoning processes during problem-solving activities.

One potential approach to addressing these learning challenges is the implementation of expert systems in educational contexts. Expert systems are computer-based systems designed to emulate the reasoning and decision-making processes of human experts when solving domain-specific problems (Giarratano & Riley, 2005; Jackson, 1999). In educational applications, expert systems can provide procedural guidance, diagnose learner errors, and offer explanations related to problem-solving processes. Therefore, such systems have the potential to function not merely as computational tools but also as intelligent tutoring systems capable of supporting students' conceptual understanding.

The development of intelligent tutoring systems and conversational learning agents is closely associated with constructivist learning theory and scaffolding principles. Constructivist perspectives emphasize that learners actively construct understanding through interaction, feedback, and guided learning experiences. In addition, scaffolding theory highlights the importance of providing structured support during problem-solving processes until learners gradually develop independent understanding and competence. In this regard, chatbot-based expert systems can facilitate interactive learning processes by providing step-by-step guidance, adaptive feedback, and reasoning explanations that support students in constructing conceptual understanding during electrical circuit analysis activities.

Despite the increasing development of AI-supported educational technologies, several limitations remain evident in previous studies. Existing studies on educational chatbots have primarily focused on communication support, student engagement, language learning, or general learning assistance (Kuhail et al., 2022; Pérez-Marín, 2021). Meanwhile, many learning applications in electrical engineering education mainly provide simulations or final numerical solutions without offering structured reasoning guidance that helps students understand problem-solving procedures conceptually. Previous research has also rarely integrated rule-based expert reasoning, chatbot interaction, and conceptual scaffolding specifically for DC electrical circuit analysis learning.

Therefore, a research gap still exists regarding the development of chatbot-based expert systems capable of functioning simultaneously as interactive conversational agents, rule-based reasoning systems, and conceptual learning assistants in electrical circuit analysis education. Addressing this gap is important because students require not only access to answers but also guided reasoning processes that can help them understand how and why a particular solution is obtained.

Based on these considerations, this study aims to develop a chatbot-based expert system for DC circuit analysis learning in electrical engineering education. The developed system is designed to provide structured step-by-step problem-solving guidance, deliver immediate feedback on student errors, and support students in understanding conceptual and procedural reasoning during circuit analysis activities.

The integration of chatbot interaction with rule-based expert reasoning is expected to provide more interactive, accessible, and adaptive learning assistance similar to consultation with a virtual tutor.

The novelty of this study lies in the integration of rule-based expert reasoning, chatbot interaction, and conceptual guidance within a single learning support system specifically designed for DC circuit analysis learning. Unlike many existing educational applications that primarily provide simulations or direct answers, the proposed system emphasizes guided reasoning processes and procedural scaffolding to support conceptual understanding. Therefore, this study contributes not only to the development of AI-assisted learning media in electrical engineering education but also to the advancement of intelligent tutoring approaches that promote independent learning, conceptual understanding, and analytical reasoning skills.

Accordingly, this study addresses the following research questions:

1. How valid is the chatbot-based expert system for DC circuit learning?
2. How practical is the chatbot-based expert system from students' perspectives?
3. How effective is the chatbot-based expert system in improving students' conceptual understanding of DC circuit analysis?

2. METHODS

This study employed a Research and Development (R&D) approach aimed at developing a chatbot-based expert system to support students in learning direct current (DC) circuit analysis. The study adopted the 4D development model proposed by Thiagarajan et al., which consists of four stages: define, design, develop, and disseminate. The 4D model was selected because it provides a systematic framework for developing instructional media through iterative analysis, design, validation, revision, and implementation processes. In addition, the model is widely used in educational product development studies because it enables researchers to refine learning products based on expert evaluation and user feedback.

The study applied a quantitative descriptive approach supported by qualitative data. Quantitative data were used to evaluate the validity, practicality, and effectiveness of the developed system, while qualitative data obtained from expert suggestions and student responses were used to enrich the interpretation of the findings. Furthermore, the effectiveness test employed a one-group pretest–posttest design to determine improvements in students' conceptual understanding after using the developed chatbot-based expert system.

2.1 Development Procedure

2.1.1 Define Stage

The define stage aimed to identify instructional problems and determine the learning requirements for the developed system. At this stage, preliminary observations were conducted during the 2024/2025 academic year in Basic Electrical Circuit courses at two higher education institutions. The activities included classroom observations, analysis of students' learning outcomes, and literature reviews related to conceptual difficulties in DC circuit analysis learning. The findings indicated that many students experienced difficulties in understanding Ohm's Law, Kirchhoff's Laws, and systematic circuit analysis procedures. These results became the basis for determining the specifications and instructional objectives of the developed chatbot-based expert system.

2.1.2 Design Stage

The design stage focused on planning the structure and instructional flow of the system. During this stage, the system architecture, chatbot interaction flow, learning content, and problem-solving procedures were designed. The instructional materials covered Ohm's Law, Kirchhoff's Current Law (KCL), Kirchhoff's Voltage Law (KVL), series circuits, and parallel circuits. In addition, research instruments such as expert validation sheets, usability questionnaires, and pretest–posttest instruments were designed during this stage.

2.1.3 Develop Stage

The development stage involved implementing the chatbot-based expert system and evaluating its quality through expert validation and student trials. The system was developed using the Streamlit framework as a web-based interactive learning platform. After the development process was completed, the system was validated by experts in electrical engineering education and educational media. Suggestions and feedback from validators were used to revise and improve the developed system before conducting implementation trials with students.

2.1.4 Disseminate Stage

The disseminate stage in this study was conducted in a limited form. The developed system was introduced through limited academic dissemination activities, including demonstrations in educational discussions and sharing through digital learning platforms accessible to students and lecturers within the study context. Therefore, the dissemination process was not conducted on a large institutional or commercial scale.

2.2 System Architecture and Reasoning Mechanism

The developed system is a chatbot-based expert system designed to support students in understanding conceptual and procedural aspects of DC circuit analysis. The system architecture consists of four primary components: the user interface, knowledge base, inference engine, and visual circuit analysis module.

The user interface was implemented as an interactive web-based application that allows students to interact with the system through conversational input. The application provides three primary learning modules: a theoretical analysis module, a DC circuit calculation module, and a circuit image analysis module. The theoretical module allows students to ask conceptual questions regarding electrical circuit principles, while the calculation module performs numerical analysis using Ohm's Law and Kirchhoff's Laws. The visual analysis module enables users to upload images of electrical circuits for conceptual interpretation.

The knowledge base contains concepts and procedural rules related to DC circuit analysis, including Ohm's Law, Kirchhoff's Current Law, Kirchhoff's Voltage Law, and the characteristics of series and parallel circuits. These concepts were organized into rule-based problem-solving procedures that allow the system to provide step-by-step explanations and conceptual guidance.

The reasoning mechanism applied in the chatbot system primarily used rule-based reasoning. User responses and numerical problem-solving processes were generated based on predefined rules and logical procedures stored in the knowledge base. Therefore, the system did not employ generative artificial intelligence or large language models for conceptual explanations and problem-solving activities.

However, artificial intelligence technology from OpenRouter was integrated specifically within the image analysis module to assist in interpreting circuit images uploaded by users. This feature was limited to visual recognition and interpretation of circuit diagrams. The AI-based image analysis module was used only to identify visual circuit components and support conceptual interpretation, while the reasoning and instructional guidance processes remained rule-based. The image analysis feature may have limitations when users upload low-quality images, incomplete circuit diagrams, or unclear symbols.

The overall architecture of the developed chatbot-based expert system, interaction workflow, and reasoning mechanism are presented in Figures 1, 2, and 3.

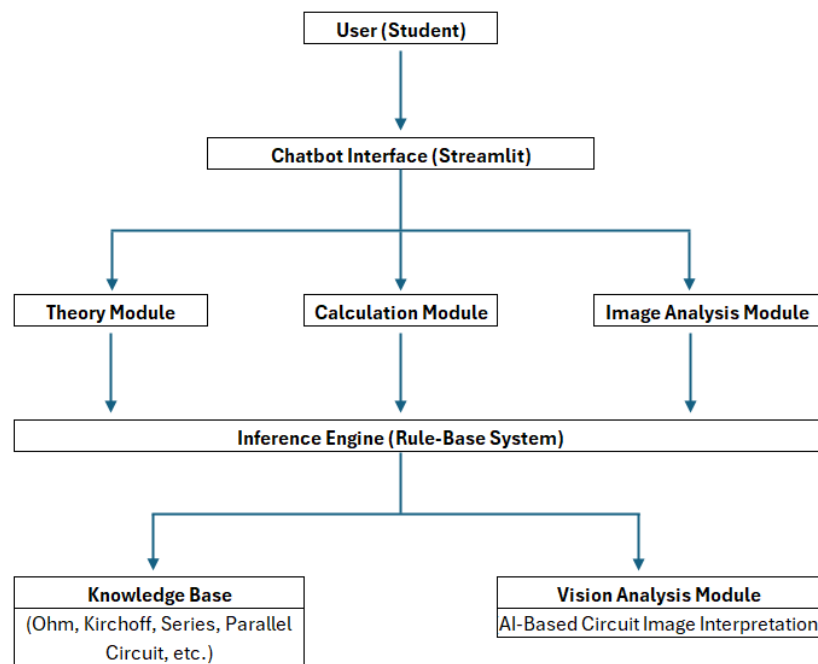


Figure 1. Architecture of the Chatbot-Based Expert System for DC Circuit Learning

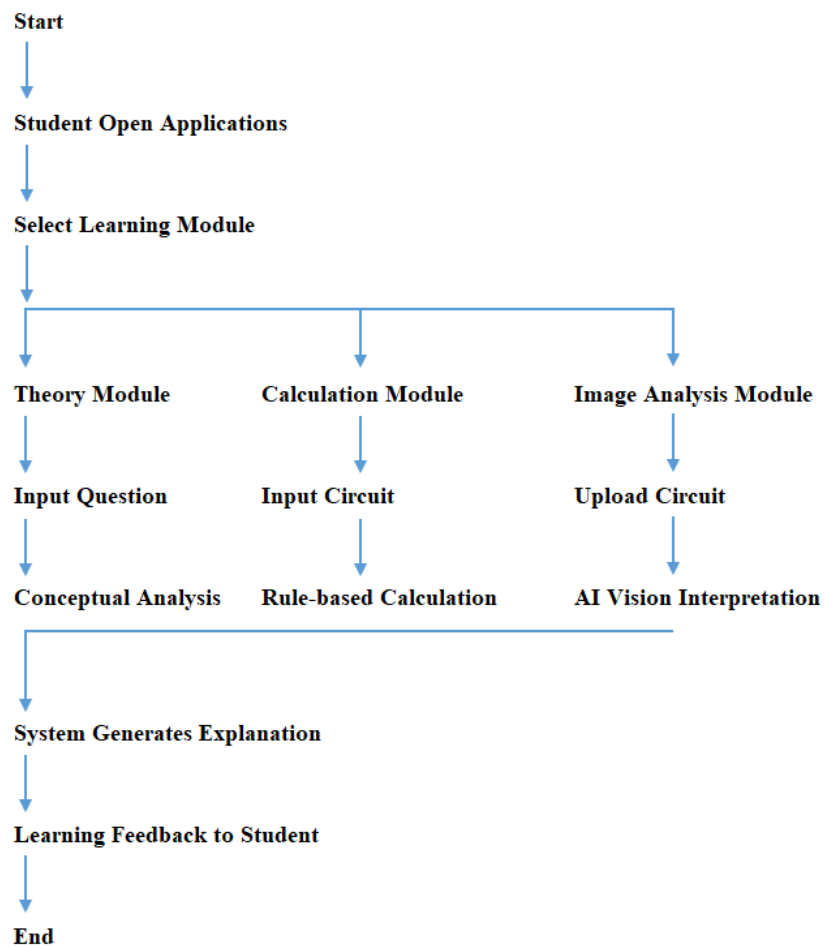


Figure 2. Interaction Flow of the Chatbot-Based Learning System.

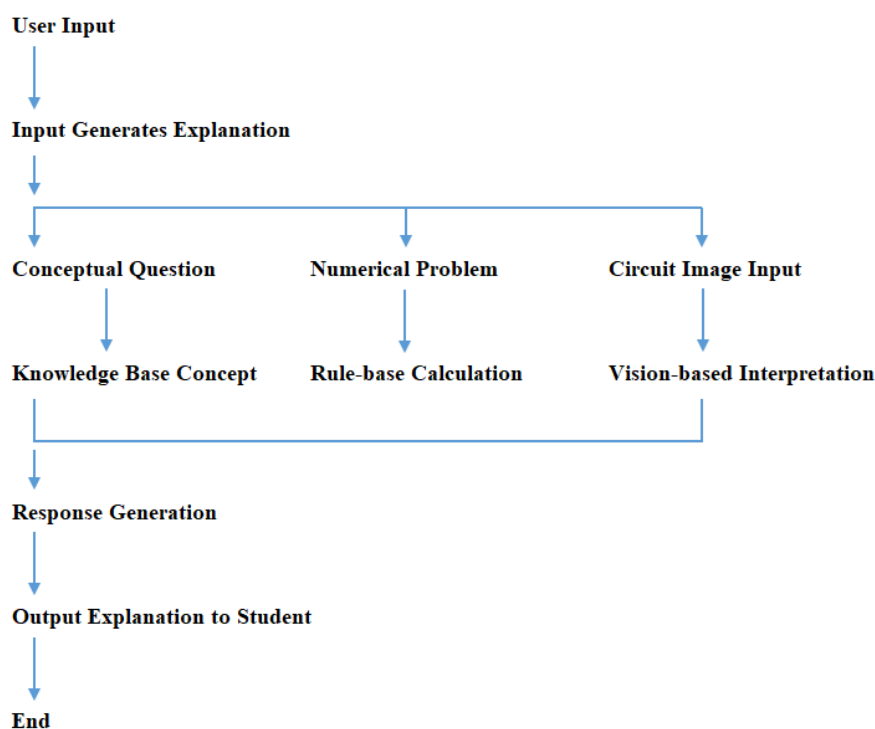


Figure 3. Rule-Based Reasoning Mechanism in the Expert System

2.3 Participants

The participants involved in this study consisted of expert validators and undergraduate students from an Electrical Engineering Education program at a public university in Indonesia. The student participants were second-year undergraduate students who had taken or were currently enrolled in a Basic Electrical Circuit course. The participants generally had prior introductory knowledge of DC circuit concepts, including Ohm's Law and basic circuit calculations.

Participants were selected using purposive sampling based on several criteria: (1) students had studied or were studying DC circuit analysis topics, (2) students were willing to participate voluntarily in the study, and (3) students were able to access and operate the web-based learning system. The expert validators consisted of one subject-matter expert in electrical engineering and two experts in educational media development. The validators were selected purposively based on their academic expertise, teaching experience, and involvement in instructional media evaluation and electrical engineering education.

2.4 Ethical Considerations

This study adhered to ethical principles in educational research. Before data collection, all participants were informed about the objectives and procedures of the study. Participation was voluntary, and students were allowed to withdraw from the study at any stage without academic consequences. Informed consent was obtained from all participants prior to the implementation process. In addition, participant anonymity and confidentiality were maintained throughout data collection, analysis, and reporting.

2.5 Research Instruments

The instruments used in this study consisted of expert validation sheets, practicality questionnaires, and pretest–posttest instruments.

2.5.1 Expert Validation Sheets

The expert validation instrument was designed to evaluate the developed system in terms of content quality, interface design, instructional suitability, system functionality, and clarity of learning

guidance. The validation sheets used a 5-point Likert scale ranging from 1 (very inappropriate) to 5 (very appropriate).

2.5.2 Practicality Questionnaire

The practicality questionnaire was administered to students after using the developed system. The questionnaire measured several indicators, including ease of use, interface attractiveness, clarity of explanations, usefulness of feedback, and overall learning support. The questionnaire used a 5-point Likert scale.

2.5.3 Pretest and Posttest Instruments

The pretest and posttest instruments were designed to measure students' conceptual understanding of DC circuit analysis. The test items covered Ohm's Law, Kirchhoff's Laws, series circuits, and parallel circuits. Example test items included determining current values using Kirchhoff's Current Law and analyzing voltage distribution in series circuits. The pretest and posttest instruments were validated through expert review to ensure content relevance and alignment with learning objectives.

2.5.4 Learning Intervention Procedure

The implementation trial was conducted during DC circuit learning activities in the Basic Electrical Circuit course. Students used the chatbot-based expert system during learning sessions to analyze conceptual and numerical DC circuit problems. During the implementation, students interacted with the chatbot to obtain procedural guidance, conceptual explanations, and feedback regarding their answers.

The instructor acted as a facilitator who supervised learning activities, provided general instructions regarding system usage, and assisted students when technical difficulties occurred. However, the instructor did not directly provide solutions to the circuit problems during chatbot interaction activities because students were encouraged to utilize the developed system independently.

2.6 Data Analysis

Quantitative data obtained from validation sheets, practicality questionnaires, and learning outcome tests were analyzed using several techniques. The validity of the developed system was analyzed using Aiken's V coefficient to determine the degree of agreement among validators regarding the relevance of each assessment item. Where s represents the validator score adjusted to the lowest category, n represents the number of validators, and c represents the number of rating categories. The validity criteria were interpreted as follows: values above 0.80 were categorized as highly valid, values between 0.60 and 0.80 were categorized as valid, and values below 0.60 indicated low validity.

The practicality of the developed system was analyzed by converting questionnaire scores into percentage values. Practicality percentages above 85% were categorized as very practical, percentages between 70%–85% were categorized as practical, and percentages below 70% indicated lower practicality.

The effectiveness of the developed system was evaluated using normalized gain (N-gain) and a paired sample t-test. The N-gain interpretation criteria were categorized as high ($g > 0.70$), moderate ($0.30 \leq g \leq 0.70$), and low ($g < 0.30$).

Prior to conducting the paired sample t-test, the normality of difference scores was tested using the Shapiro–Wilk normality test. The paired sample t-test was subsequently used to determine whether significant differences existed between students' pretest and posttest scores after using the chatbot-based expert system.

Although the study demonstrated improvements in students' conceptual understanding, the absence of a control group in the one-group pretest–posttest design constitutes a methodological limitation. Therefore, the findings should be interpreted within the context of the implemented learning intervention.

3. FINDINGS AND DISCUSSION

3.1 Findings

3.1.1 Expert Validation Results

The developed chatbot-based expert system was evaluated by one subject-matter expert and two media experts to determine its validity in terms of learning content, system functionality, interface quality, and instructional suitability. The validation results were analyzed using Aiken's V coefficient.

Table 1 shows that the material validation results achieved high validity across all evaluated aspects. The overall mean score was 4.75 out of 5.00, with an average Aiken's V value of 0.94, indicating that the developed system met the criteria of "very valid." The highest validity values were identified in the expert system and interactivity aspects ($V = 1.00$), suggesting that the chatbot was considered capable of providing structured reasoning guidance and interactive learning support.

Table 1. Results of Material Expert Validation

No.	Aspect	Item Range	Mean Score	Mean Aiken's V	Category
1	Alignment with Learning Objectives	1–3	4.67	0.92	Very Valid
2	Content Accuracy	4–8	4.8	0.95	Very Valid
3	Content Currency	9–10	4.5	0.88	Very Valid
4	Expert System Aspect	11–12	5	1	Very Valid
5	Chatbot Aspect	13–14	4.5	0.88	Very Valid
6	Interactivity Aspect	15–16	5	1	Very Valid
Overall Average		1–16	4.75	0.94	Very Valid

The media expert validation results also demonstrated a high level of validity. As presented in Table 2, the developed system achieved an overall mean score of 4.93 and an average Aiken's V value of 0.96, indicating that the user interface, functionality, and usability aspects were considered highly appropriate for learning implementation.

Table 2. Results of Media Expert Validation

No.	Aspect	Item Range	Validator		Mean Score	Aiken's V	Category
			1	2			
1	User Interface	1–5	5	5	5	1	Very Valid
2	Functionality	6–11	4.5	5	4.83	0.94	Very Valid
3	Usability	12–14	5	5	5	1	Very Valid
Overall Average		1–14	4.79	5	4.93	0.96	Very Valid

Overall, the validation findings indicate that the developed chatbot-based expert system demonstrated strong validity in terms of instructional content, system functionality, and interface usability prior to classroom implementation.

3.1.2 Practicality Results

The practicality evaluation was conducted through a limited implementation involving 25 students enrolled in the Basic Electrical Circuits course. After using the chatbot system during learning activities, students completed a practicality questionnaire to assess usability, efficiency, and implementation feasibility.

The practicality results are presented in Table 3. The overall practicality percentage reached 86.30%, which falls within the "very practical" category. The highest score was identified in the usability aspect (90.00%), indicating that students perceived the chatbot interface and interaction flow as easy to use during learning activities. In addition, the efficiency and implementation feasibility

aspects also obtained high scores, suggesting that the system was considered supportive for independent learning activities.

Table 3. Practicality Test Results

No.	Aspect	Mean Score	Percentage (%)	Category
1	Usability	4.5	90	Very Practical
2	Time and Place Efficiency	4.2	84	Very Practical
3	Implementation Feasibility	4.25	85	Very Practical
Overall Average		4.32	86.3	Very Practical

These findings indicate that the developed chatbot system showed high practicality and usability for supporting learning activities in DC circuit analysis courses.

3.1.3 Learning Effectiveness Results

The effectiveness of the chatbot-based expert system was evaluated using a one-group pretest–posttest design involving 25 students. Students completed a pretest before using the chatbot system and a posttest after participating in chatbot-assisted learning activities.

Table 4 presents the classical completeness results for the pretest and posttest. Although the pretest completeness percentage was already relatively high (96.00%), the mean pretest score remained relatively low (61.20 out of 100), indicating that many students had only achieved the minimum passing criterion and had not yet demonstrated strong conceptual mastery of DC circuit analysis. After the implementation of the chatbot-assisted learning activities, the posttest completeness increased to 100.00%.

Table 4. Pretest and Posttest Results

Test	Student Achieving ($\geq C$)	Total Students	Completeness (%)	Category
Pretest	24	25	96%	Complete
Posttest	25	25	100%	Complete

To further examine improvements in students' conceptual understanding, a normalized gain (N-gain) analysis was conducted. The results presented in Table 5 indicate that the mean score increased from 61.20 in the pretest to 73.64 in the posttest, producing an N-gain value of 0.32, which falls within the moderate category.

Table 5. Normalized Gain Analysis Results

Test	Mean Score	Maximum Score
Pretest	61.2	100
Posttest	73.64	100
N-Gain (g)	0.32	
Category	Moderate	

The moderate N-gain result suggests that the chatbot-assisted learning activities were associated with measurable improvements in students' conceptual understanding, although the magnitude of improvement remained moderate.

To determine whether the improvement in learning outcomes was statistically significant, a paired sample t-test was conducted. The results are presented in Table 6.

Table 6. Paired Sample t-Test Results

Pair	Mean Difference	Std. Dev.	Std. Error Mean	t	df	Sig. (2-tailed)
Posttest – Pretest	12.44	2.20	0.44	28.27	24	< 0.001

The paired sample t-test demonstrated a statistically significant difference between pretest and posttest scores, $t(24) = 28.27$, $p < .001$. In addition, the effect size analysis using Cohen's d indicated a large effect size ($d = 5.65$), suggesting that the intervention was associated with substantial differences

between pretest and posttest performance. However, because the study employed a one-group pretest–posttest design without a control group, these findings should be interpreted cautiously within the context of the limited implementation setting.

3.2 Discussion

This development study aimed to produce a chatbot-based expert system that is valid, practical, and capable of supporting learning activities in the Basic Electrical Circuits course. Overall, the findings indicate that the developed system met the validity and practicality criteria and showed potential to support students' conceptual understanding of DC circuit analysis within the context of the implemented learning activities. These findings are consistent with previous studies suggesting that AI-assisted learning media should undergo validity, practicality, and effectiveness evaluation before being implemented in educational settings (Han et al., 2022; Kuhail et al., 2022; Deng & Yu, 2023)

From the validity perspective, the expert evaluation results demonstrated that the developed system achieved high validity in terms of content suitability, instructional design, and system functionality. The high content validity indicates that the learning materials and problem-solving procedures implemented in the chatbot were aligned with the learning objectives and conceptual requirements of DC circuit analysis. In addition, the iterative revision process based on expert feedback contributed to improving the instructional and technical quality of the developed system. These findings support previous studies emphasizing that content validity and expert evaluation are important components in the development of AI-based educational systems and intelligent learning media (Kuhail et al., 2022; Wollny et al., 2021).

From the practicality aspect, the findings indicate that students perceived the chatbot system as easy to use, responsive, and supportive for learning activities. High practicality scores suggest that the interface design, interaction flow, and response mechanisms were sufficiently accessible for students during learning implementation. This finding is consistent with previous research showing that usability, navigation clarity, and interaction quality strongly influence user acceptance of chatbot-assisted learning technologies (Smutny & Schreiberova, 2020; Chiu, 2023). Furthermore, several students reported that the chatbot allowed them to obtain explanations and feedback more quickly compared to conventional classroom questioning processes. Expert feedback also indicated that the conversational interface helped organize procedural learning activities more systematically. These qualitative responses suggest that responsive interaction and accessible feedback may contribute positively to students' learning experiences.

Regarding effectiveness, the findings showed improvements in students' posttest scores after the implementation of the chatbot-assisted learning activities. The normalized gain score was categorized as moderate, indicating that the developed system was associated with measurable improvement in conceptual understanding, although the magnitude of improvement remained limited. The paired sample t-test also demonstrated a statistically significant difference between pretest and posttest scores. However, these findings should be interpreted cautiously because the study employed a one-group pretest–posttest design without a control group.

An important consideration in interpreting the effectiveness findings is the possibility of a ceiling effect. The pretest completeness percentage was already relatively high before the intervention, indicating that many students had already achieved the minimum passing criterion at the beginning of the study. Nevertheless, the relatively low mean pretest score suggests that students' conceptual understanding was still limited despite meeting administrative passing standards. Therefore, the observed improvement may reflect enhancement in conceptual depth and procedural understanding rather than merely improvement in passing rates. This finding indicates that the chatbot-based expert system may have provided additional conceptual support even when baseline completeness levels were already high.

The moderate improvement observed in this study may be related to several instructional characteristics of the developed chatbot system. First, the chatbot provided step-by-step guidance

during problem-solving activities, allowing students to follow structured analytical procedures in solving DC circuit problems. Second, the system delivered immediate feedback regarding user responses, which may have helped students identify and correct conceptual errors more efficiently. Third, the conversational interaction enabled students to ask questions repeatedly and obtain explanations interactively during learning activities. Finally, the accessibility of the chatbot system supported more independent learning because students could access assistance without depending entirely on instructor availability. These findings are consistent with previous studies reporting that intelligent tutoring systems and educational chatbots can support conceptual learning through adaptive feedback, guided reasoning, and interactive learning assistance (Alemdag, 2025; Guan et al, 2025; Laun & Wolff, 2025).

From a theoretical perspective, these findings are consistent with constructivist learning principles, which emphasize that knowledge is actively constructed through interaction, feedback, and guided learning experiences. The chatbot system facilitated active learning processes by providing procedural scaffolding, conceptual clarification, and interactive dialogue during problem-solving activities. Such support mechanisms are closely related to scaffolding theory, where learners receive structured assistance while gradually developing independent understanding and problem-solving abilities. Previous studies have similarly suggested that educational chatbots and intelligent tutoring systems can strengthen conceptual understanding and learner engagement through adaptive interaction and continuous feedback processes (Kuhail et al., 2022; Pérez-Marín, 2021).

The findings also indicate that the developed system may support self-regulated learning. Students were able to access explanations, procedural guidance, and corrective feedback independently during learning activities. This flexibility potentially encouraged students to manage their own learning processes more autonomously. Similar findings have been reported in recent studies indicating that AI-assisted learning technologies can support self-regulated learning through personalized interaction, flexible access, and immediate instructional feedback (Habibi et al., 2023; Baidoo-anu & Ansah, 2023).

Despite these promising findings, several limitations should be acknowledged. First, the study involved a relatively small number of participants from a single educational context, which limits the generalizability of the findings. Second, the study employed a one-group pretest–posttest design without a control group; therefore, causal conclusions regarding the effectiveness of the intervention should be interpreted cautiously. Third, the intervention period was relatively short, limiting the ability to evaluate long-term learning retention and sustained learning effects. Fourth, the possibility of a test familiarity effect may have influenced posttest performance because students completed similar conceptual assessments before and after the intervention. In addition, the image-analysis feature integrated through OpenRouter AI was limited to visual interpretation support and may not consistently interpret unclear or incomplete circuit images accurately.

Overall, the findings suggest that the developed chatbot-based expert system showed potential as a supportive learning medium for DC circuit analysis learning within electrical engineering education. The study contributes to the growing implementation of AI-assisted instructional technologies in vocational and engineering education, particularly in supporting interactive, concept-oriented, and independent learning experiences. Future studies are recommended to involve larger samples, longer intervention periods, and experimental designs with control groups to obtain stronger evidence regarding the educational impact of chatbot-assisted learning systems.

4. CONCLUSION

This study developed and evaluated a chatbot-based expert system designed to support learning in DC circuit analysis courses. The findings indicate that the developed system demonstrated high validity and practicality and showed potential to improve students' conceptual understanding of DC circuit analysis within the context of the implemented learning activities. The system was considered appropriate in terms of content quality, usability, and instructional support for learning basic electrical circuit concepts.

The findings also suggest that the integration of rule-based expert systems and conversational interaction may support learning through step-by-step guidance, immediate feedback, and accessible learning assistance. Therefore, the developed system has practical implications for lecturers, vocational education institutions, and instructional media developers seeking to integrate AI-assisted learning technologies into engineering and vocational education environments.

However, the findings should be interpreted cautiously due to several study limitations. The study involved a relatively small sample from a single educational setting and employed a one-group pretest–posttest design without a control group. In addition, the intervention period was relatively short, which limits conclusions regarding long-term learning impact and generalizability.

Future research is recommended to evaluate the developed chatbot system using experimental designs involving control groups and larger, more diverse participant samples. Further studies may also investigate long-term retention effects, examine students' problem-solving processes in greater depth, and enhance the adaptive feedback capabilities of the chatbot system to support more personalized learning experiences in engineering education.

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