Jupiter: Jurnal Pendidikan Terapan
Homepage : https://journal.diginus.id/jupiter/index
Email: jurnalpendidikanterapan@gmail.com

p-ISSN : 2985-3214; e-ISSN : 2964-3171
Jupiter, Vol. 4, No. 3, July 2026
Page 677-689

Case-Based Digital Learning Media for Enhancing Troubleshooting Skills in Refrigeration and Air Conditioning Education

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ARTICLE INFO

Article history:
Submitted: July 02, 2026
Final Revised: July 20, 2026
Accepted: July 28, 2026
Published: July 31, 2026

Keywords:
Case-Based Learning; Digital Learning Media; Refrigeration and Air Conditioning Education; Troubleshooting Skills; Vocational Education.

ABSTRACT

Purpose: This study aimed to develop and evaluate case-based digital learning media designed to enhance students' troubleshooting skills in refrigeration and air-conditioning education. **Methods**: The study employed a research and development approach using the ADDIE-ID model, comprising the Analyze, Design, Develop, Implement, Evaluate, and Integrate and Disseminate stages. The resulting web-based digital learning media, COOLTRACE (Case-Based Learning for Refrigeration Troubleshooting), was evaluated by two subject matter experts and two media experts. Practicality testing involved 20 undergraduate students, while effectiveness testing was conducted with 81 students using a one-group pretest–posttest design. The data were analyzed using descriptive statistics and normalized gain (N-Gain) analysis. **Findings**: COOLTRACE obtained validity scores of 97.50% from subject matter experts and 97.22% from media experts, indicating that the product met the required instructional and technical quality standards. The overall practicality score was 93.69%, demonstrating that students could access and use the media with minimal difficulty. Students' mean scores increased from 71.46 on the pretest to 96.69 on the posttest, with a mean N-Gain of 0.84, classified as high. These findings indicate a substantial improvement in students' troubleshooting knowledge and diagnostic decision-making following the intervention. **Research Implications**: COOLTRACE provides a practical digital learning resource for supporting systematic troubleshooting practice, particularly in learning contexts where opportunities for repeated fault-diagnosis activities using physical equipment are limited. **Originality**: This study contributes interactive web-based digital learning media that integrates authentic cases, guided diagnosis, corrective action sequencing, and immediate feedback within a systematic troubleshooting learning process.

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Doi: https://doi.org/10.61255/jupiter.v4i3.1698

INTRODUCTION

The rapid advancement of digital technologies in the Industry 4.0 era has transformed vocational education from a predominantly knowledge-oriented approach toward competency-based learning that emphasizes twenty-first-century skills. Engineering graduates are expected not only to master theoretical concepts but also to demonstrate critical thinking, problem-solving, decision-making, collaboration, and adaptability to technological and industrial change. Research in vocational education indicates that digital learning platforms, simulation technologies, and game-based learning environments can improve students' academic performance, engagement, and motivation (Dahalan et al., 2023). These global demands are equally relevant in Indonesia, where the development of competitive human resources has become a national priority to support the Indonesia Emas 2045 vision. Nevertheless, Indonesia continues to face significant educational challenges, including curriculum dynamics, educational inequality, teacher shortages, infrastructure limitations, and increasing dropout rates, which hinder efforts to improve the quality of education (Samala et al., 2024). Consequently, there is an increasing need for innovative instructional approaches that effectively integrate digital technology with the development of higher-order problem-solving skills in vocational education.

In engineering education, troubleshooting is widely recognized as a core professional competency that distinguishes conceptual understanding from the ability to solve real technical problems. Troubleshooting requires learners to identify technical faults, analyze their causes, and determine appropriate corrective actions under practical constraints. Diong et al. emphasized that troubleshooting is an integral component of engineering practice because engineers must be able to identify and resolve technical problems strategically within time-constrained situations. Similarly, Fatokun and Gumbo found that although troubleshooting is regarded as an essential competency for engineering practice, it is often underrepresented in engineering curricula, which tend to emphasize design-oriented problem solving rather than technical troubleshooting. Their findings suggest that engineering graduates may remain underprepared for professional practice unless troubleshooting is deliberately integrated into engineering curricula through sustained instructional interventions and authentic practical experiences (Diong et al., 2021; Fatokun & Gumbo, 2024). Therefore, refrigeration and air conditioning education should provide learning experiences that strengthen conceptual knowledge, diagnostic reasoning, and decision-making through authentic troubleshooting activities relevant to industrial practice.

Although troubleshooting has long been recognized as an essential competency in engineering education, developing this capability remains challenging in refrigeration and air conditioning (RAC) learning environments. Effective troubleshooting instruction requires repeated opportunities for students to observe system behavior, identify technical faults, analyze possible causes, formulate and test diagnostic hypotheses, and determine appropriate corrective actions under realistic operating conditions. Practice-based engineering education emphasizes learning through authentic professional contexts that enable students to participate in engineering practice and progressively develop professional capabilities (Mann et al., 2021). In RAC education, however, opportunities for repeated troubleshooting practice are frequently constrained by limited laboratory facilities, restricted instructional time, operational costs, safety considerations, and the potential risk of damaging equipment during fault-diagnosis activities. To address these challenges, vocational engineering education has increasingly explored technology-enhanced learning environments, including mobile mixed reality, to complement laboratory-based instruction, particularly when access to physical equipment is limited (Smith et al., 2021). Similarly, mixed-reality applications developed for HVAC learning factories have demonstrated the potential of these technologies to support engineering education by enabling learners to visualize HVAC system behavior and interact with cyber-physical learning environments (Czarski et al., 2020). Nevertheless, technological innovation alone is insufficient to develop troubleshooting competence. Digital learning environments should also incorporate instructional strategies that systematically cultivate diagnostic reasoning, evidence-based decision-making, and structured problem-solving processes rather than merely presenting equipment operation or procedural demonstrations.

Advances in digital technology have created new opportunities to overcome many of the practical limitations associated with engineering instruction through interactive learning environments. Digital learning platforms, virtual laboratories, simulation technologies, mixed reality, and mobile learning applications enable students to access practical learning experiences beyond conventional laboratory settings, visualize technical processes that are difficult to observe directly, and engage in repeated practice without exposing learners or equipment to unnecessary risks. A systematic review of vocational education identified technology-enhanced learning environments, including digital and game-based learning approaches, as promising strategies for improving students' academic performance, engagement, and learning motivation (Dahalan et al., 2023). Likewise, mobile mixed-reality technology has demonstrated considerable potential for supporting fault-diagnosis activities by providing structured guidance that assists novice learners in performing technical tasks when access to physical laboratory facilities is limited (Smith et al., 2021). Nevertheless, the digital learning approaches reported in these studies primarily emphasize content delivery, visualization, procedural guidance, or simulation-based practice. Although these features effectively enhance conceptual understanding and learner engagement, they do not necessarily support the development of diagnostic reasoning, hypothesis generation, evidence-based decision-making, and reflective evaluation that characterize authentic troubleshooting practice. Consequently, there remains a need for digital learning environments that deliberately integrate authentic engineering cases with structured diagnostic activities to foster systematic troubleshooting competence in vocational engineering education.

Case-Based Learning (CBL) provides a strong pedagogical foundation for addressing these instructional needs by organizing learning around contextualized engineering cases that closely resemble professional practice. Through CBL, students actively investigate authentic problems by interpreting available evidence, exploring alternative explanations, evaluating possible solutions, and reflecting on their reasoning throughout the problem-solving process. Rather than emphasizing procedural memorization, CBL promotes active knowledge construction by situating learning within meaningful professional contexts. Lavi & Martí, (2023) explained that CBL contextualizes discipline-specific knowledge through authentic case implementations while gradually increasing learner autonomy across successive learning activities. They further observed that, despite its educational advantages, CBL remains less frequently implemented in undergraduate engineering education than project-based or problem-based learning. Complementary evidence from systematic reviews indicates that problem-based and project-based learning environments contribute positively to higher-order thinking and critical-thinking development, although considerable variation remains in how these competencies are conceptualized and assessed across studies (Loyens et al., 2023). Likewise, adaptations of problem-based learning that explicitly integrate critical-thinking activities have consistently demonstrated positive effects on students' critical-thinking development (Yu & Zin, 2023). Collectively, these findings suggest that CBL offers considerable potential for troubleshooting education because both emphasize evidence analysis, evaluation of alternative explanations, and systematic decision-making when solving authentic engineering problems.

Previous studies have investigated various forms of digital learning technology including web-based learning media, virtual laboratories, simulation systems, mixed-reality applications, game-based learning environments, and digital diagnostic tools to improve engineering and vocational education. Other studies have focused on the implementation of Case-Based Learning as a pedagogical approach for enhancing critical thinking, problem-solving, communication, creativity, and professional decision-making. However, these two research streams have largely evolved independently. Research on digital learning has predominantly concentrated on improving accessibility, visualization, learner engagement, procedural guidance, and learning motivation, whereas CBL research has primarily emphasized contextual learning, collaborative discussion, case analysis, and reflective learning processes. Based on the literature reviewed in this study, relatively limited attention has been devoted to digital learning environments that integrate authentic engineering cases with the complete troubleshooting process, including symptom identification, causal analysis, diagnostic hypothesis generation, inspection planning, evaluation of alternative diagnoses, and determination of corrective actions. Furthermore, studies specifically addressing troubleshooting instruction in refrigeration and air conditioning education remain limited. These observations indicate the need for instructional innovations that combine interactive digital technology with authentic case-based learning to systematically develop troubleshooting competence rather than treating instructional technology and pedagogy as separate components.

Based on the foregoing review, three principal research gaps can be identified. First, although numerous digital learning media have been developed for engineering education, most primarily emphasize content delivery, visualization, procedural simulation, virtual laboratories, or guided technical practice, while relatively few integrate digital learning environments with Case-Based Learning to systematically cultivate troubleshooting competence. Second, previous studies on Case-Based Learning have mainly examined broad educational outcomes, such as critical thinking, problem-solving, knowledge acquisition, creativity, learner engagement, and satisfaction, whereas diagnostic reasoning within refrigeration and air conditioning systems has received comparatively limited attention. Third, few studies have developed and comprehensively evaluated interactive case-based digital learning media specifically designed for refrigeration and air conditioning education in terms of validity, practicality, and effectiveness. Therefore, this study aims to develop and evaluate an interactive case-based digital learning medium to enhance students' troubleshooting skills in refrigeration and air conditioning education. Unlike previous studies that primarily examined digital learning technologies or Case-Based Learning as separate instructional approaches, the proposed learning medium integrates authentic engineering cases with symptom identification, causal analysis, diagnostic reasoning, inspection planning, evaluation of alternative solutions, corrective-action sequencing, and evidence-based decision-making within a single interactive digital learning environment. By combining the pedagogical strengths of Case-Based Learning with interactive digital technology, this study is expected to contribute to the advancement of vocational engineering education by providing a validated instructional model that supports the development of industry-relevant troubleshooting competence.

METHOD

This study employed a Research and Development (R&D) approach to develop and evaluate a Case-Based Learning (CBL)-based digital learning media for improving students' troubleshooting skills in Refrigeration Engineering. The development followed the ADDIE-ID instructional design model, consisting of the Analyze, Design, Develop, Implement, Evaluate, and Integrate and Disseminate stages. The quality of the developed media was evaluated in terms of its validity, practicality, and effectiveness.

The study was conducted in the Electrical Engineering Education Study Program, Universitas Negeri Makassar. Three lecturers participated in the needs analysis. Product validation involved two content experts and two media experts selected purposively according to their expertise in refrigeration engineering, instructional media, and educational technology. The practicality evaluation involved 20 undergraduate students, while the effectiveness evaluation employed a one-group pretest-posttest design involving 81 students enrolled in the Refrigeration Engineering course. Purposive sampling was applied because all participants represented the intended users of the developed learning media.

The development procedure followed the ADDIE-ID model. During the analysis stage, curriculum requirements, student characteristics, laboratory conditions, and instructional problems related to troubleshooting were identified through interviews and document analysis. The design stage involved preparing the learning structure, user interface, storyboard, troubleshooting scenarios, and assessment instruments based on the Case-Based Learning approach. A web-based learning media was subsequently developed using HTML, CSS, and JavaScript. The prototype was validated by content and media experts, revised according to their recommendations, and implemented in a limited trial. Formative evaluation was conducted throughout the development process, while summative evaluation examined the validity, practicality, and effectiveness of the final product.

Data were collected using interview guidelines, expert-validation sheets, a practicality questionnaire, and troubleshooting achievement tests. Interview guidelines were used during the needs analysis. Expert-validation sheets assessed the quality of the learning content and media design using a four-point rating scale. The practicality questionnaire measured students' perceptions of the media in terms of ease of use, ease of learning, efficiency, attractiveness, and usefulness. The effectiveness of the developed media was evaluated using a 25-item multiple-choice troubleshooting test administered as pretest and posttest. The test measured students' ability to identify fault symptoms, analyze possible causes, determine inspection procedures, interpret diagnostic information, and select appropriate corrective actions. Content validity was established through expert judgment, while instrument reliability was examined using Cronbach's alpha (Cronbach, 1951).

Qualitative data obtained from interviews and expert comments were analyzed descriptively to support product revision. Quantitative data from expert validation and practicality evaluation were converted into percentages and interpreted according to the feasibility criteria proposed by Asyhari & Silvia (2016).
The effectiveness of the developed media was determined using the normalized gain (N-Gain) proposed by Hake, (1999):

$$N\text{-Gain} = \frac{S_{post} - S_{pre}}{S_{max} - S_{pre}}$$

where S_{post} is the posttest score, S_{pre} is the pretest score, and S_{max} is the maximum possible score. According to Hake (1999), N-Gain values above 0.70 indicate high improvement, values between 0.30 and 0.70 indicate moderate improvement, and values below 0.30 indicate low improvement. The developed media were considered effective when students achieved at least a moderate improvement in troubleshooting skills.

RESULTS

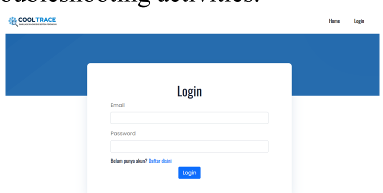
A needs analysis was conducted through curriculum analysis, interviews with three Refrigeration Engineering lecturers, a questionnaire administered to 20 students, and an analysis of student characteristics. The findings consistently indicated a common instructional need for a digital learning medium capable of systematically supporting troubleshooting competence. As summarized in Table 1, the curriculum identifies troubleshooting as a core learning outcome requiring diagnostic reasoning and structured problem-solving skills. Lecturer interviews revealed that existing learning resources adequately support practical instruction but provide limited opportunities for students to practice systematic fault diagnosis. Likewise, students expressed the need for flexible and interactive learning resources that facilitate independent troubleshooting practice, while the analysis of student characteristics indicated that students possessed sufficient digital literacy but still required instructional guidance to strengthen analytical reasoning during troubleshooting activities. Collectively, these findings established the instructional foundation for developing a Case-Based Learning-based digital learning medium that integrates authentic troubleshooting cases with structured diagnostic activities.

Table 1. Summary of the Needs Analysis

Source	Key Findings	Implications for Media Development
Curriculum analysis	Troubleshooting is a core learning outcome requiring systematic diagnosis and problem-solving skills.	The media should provide structured case-based learning activities.
Lecturer interviews	Existing learning resources support practical activities but do not provide interactive troubleshooting practice. Students still experience difficulties in diagnosing faults systematically.	The media should facilitate authentic troubleshooting exercises through Case-Based Learning.
Student questionnaire	Students reported limited opportunities to practice troubleshooting and expected flexible, interactive digital learning resources.	The media should support independent learning with interactive case simulations.
Student characteristics	Students possess basic refrigeration knowledge and digital literacy but require guidance in analytical reasoning.	The media should present a simple interface with step-by-step diagnostic guidance.

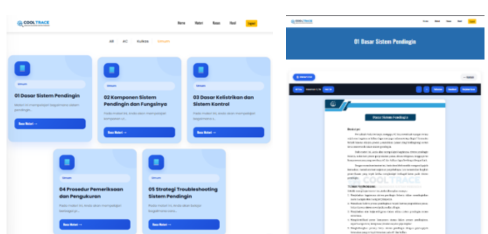
Based on the identified instructional needs, a web-based digital learning medium named COOLTRACE (Case-Based Learning for Refrigeration Troubleshooting) was developed to support troubleshooting instruction in the Refrigeration Engineering course. The application integrates conceptual learning with authentic refrigeration fault cases through a structured instructional sequence derived from the principles of Case-Based Learning. Students are guided through successive stages of case analysis, diagnostic reasoning, evaluation of alternative solutions, corrective-action planning, and reflection, thereby encouraging systematic troubleshooting rather than procedural memorization.

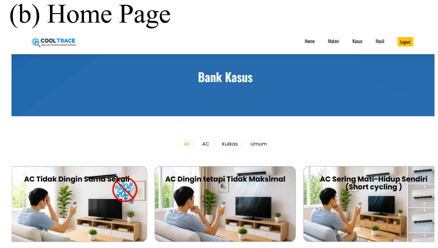
The main interface of COOLTRACE is presented in Figure 1. The application provides access to two integrated learning components, namely conceptual learning materials and an authentic case library. This interface was designed to facilitate a progressive learning process in which students first acquire the necessary conceptual knowledge before engaging in troubleshooting activities.



(a) Login Page

(b) Home Page





(c) Learning Materials Pag

(d) Case Library Page

Figure 1. Main interface of the COOLTRACE digital learning medium

Following the conceptual learning stage, students proceed to the troubleshooting activities through the case library. Each case presents a realistic refrigeration fault scenario consisting of the system condition, observed symptoms, and preliminary inspection data. These cases serve as the starting point for students to apply conceptual knowledge in diagnosing technical problems within an authentic engineering context.

The instructional workflow implemented in COOLTRACE is illustrated in Figure 2. Rather than following a linear sequence of procedural tasks, the workflow supports iterative diagnostic reasoning by allowing students to select diagnostic procedures, interpret inspection results, evaluate alternative solutions, receive immediate conceptual feedback, and revise inappropriate decisions before progressing to subsequent stages. This iterative process reflects the authentic troubleshooting practices commonly encountered in professional engineering environments while encouraging evidence-based technical decision-making.

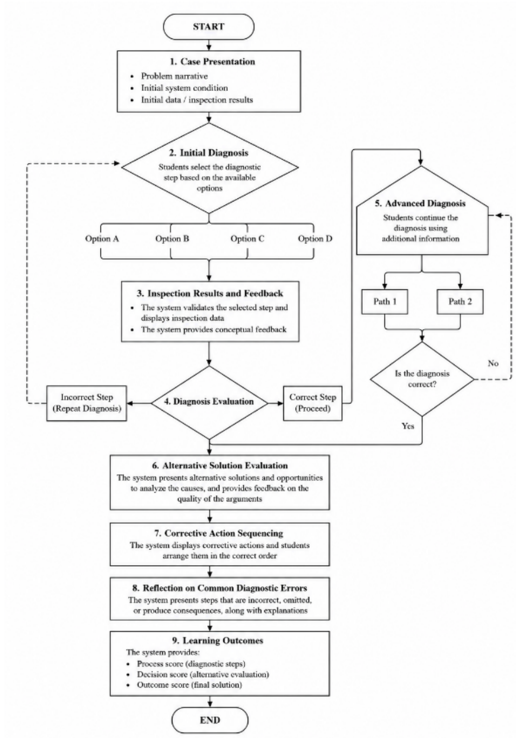


Figure 2. Instructional workflow supporting systematic troubleshooting in COOLTRACE

The completed application consists of several integrated instructional modules that collectively support conceptual learning and troubleshooting practice. As summarized in Table 2, these modules include conceptual learning materials, an authentic case library, guided diagnostic activities, immediate conceptual feedback, corrective-action sequencing, reflective learning, performance reporting, and a lecturer dashboard for managing instructional content and monitoring student progress. Together, these integrated features establish a comprehensive digital learning environment that combines conceptual understanding, authentic case analysis, guided diagnosis, formative feedback, and learning analytics within a single web-based platform.

Table 2. Main Features of the Developed Digital Learning Media

Feature	Function
Learning materials	Present fundamental concepts of refrigeration systems before troubleshooting activities.
Case library	Provides a collection of refrigeration fault cases that students can select for diagnostic practice.
Case presentation	Presents the problem narrative, system condition, symptoms, and preliminary inspection data for each selected case.
Initial diagnosis	Enables students to select the most appropriate initial diagnostic procedure based on the available case information.
Inspection results and feedback	Displays inspection data corresponding to the selected procedure and provides immediate conceptual feedback.

Feature	Function
Advanced diagnosis	Allows students to continue the diagnostic process using additional information when the initial diagnosis is insufficient.
Alternative solution evaluation	Enables students to evaluate possible causes and alternative corrective solutions.
Corrective action sequencing	Requires students to arrange the repair procedures in the correct operational sequence.
Reflection on diagnostic errors	Provides explanations of inappropriate, omitted, or consequential diagnostic decisions.
Learning outcomes	Displays students' process, decision, and final-solution scores after completing each case.
Lecturer dashboard	Supports the management of learning materials, troubleshooting cases, and students' learning records.

Overall, COOLTRACE was developed as an integrated digital learning medium that combines conceptual content, authentic case presentation, guided diagnostic activities, formative feedback, corrective action planning, and performance reporting within a single web-based system. The developed digital learning medium was evaluated by two subject matter experts and two media experts before classroom implementation to ensure its instructional and technical quality. The validation process assessed the appropriateness of the learning content, implementation of Case-Based Learning principles, pedagogical quality, interface design, usability, functionality, compatibility, and overall instructional quality. Material validation results are presented in Table 3. The overall validity score reached 97.50%, indicating that the developed learning medium was classified as very valid.

Table 3. Summary of Material Expert Validation

Aspect	Validity (%)	Category
Alignment with learning outcomes	93.75	Very valid
Content accuracy	96.88	Very valid
Integration of theory and cases	95.83	Very valid
Case-Based Learning characteristics	100.00	Very valid
Pedagogical appropriateness	100.00	Very valid
Readability and presentation	100.00	Very valid
Overall	**97.50**	**Very valid**

Material validation demonstrated excellent quality across all evaluated aspects. The highest ratings were obtained for the implementation of Case-Based Learning characteristics, pedagogical appropriateness, and readability of the learning materials, each achieving a validity score of 100%. Likewise, alignment with learning outcomes, content accuracy, and integration of theoretical concepts with authentic troubleshooting cases also received very high ratings. These findings indicate that the instructional content was well aligned with the intended learning objectives and appropriately supported the development of students' troubleshooting competence. The results of media expert validation are summarized in Table 4. The developed application achieved an overall validity score of 97.22%, indicating that the technical quality of the learning medium was also classified as very valid.

Table 4. Summary of Media Expert Validation

Aspect	Validity (%)	Category
Interface design	100.00	Very valid
Usability	93.75	Very valid
Functionality	100.00	Very valid
Compatibility	100.00	Very valid
Instructional quality	93.75	Very valid
Overall	**97.22**	**Very valid**

Media experts assigned the highest ratings to interface design, functionality, and compatibility, each achieving a perfect validity score. Usability and instructional quality were also evaluated as very valid, indicating that the application was technically reliable, easy to operate, and suitable for supporting Case-Based Learning activities. Overall, the validation results confirmed that the developed learning medium satisfied both instructional and technical quality requirements and was therefore considered appropriate for classroom implementation.

Table 5. Results of Practicality Evaluation

Aspect	Score (%)	Category
Ease of Use	93.44	Very Practical
Ease of Learning	92.19	Very Practical
Efficiency	92.50	Very Practical
Usefulness	95.31	Very Practical
Attractiveness	95.00	Very Practical
Overall	**93.69**	**Very Practical**

The results presented in Table 5 indicate that the developed learning medium achieved an overall practicality score of 93.69%, which falls within the very practical category. All evaluated aspects obtained scores above 92%, demonstrating a consistently positive response from students. The highest score was obtained for usefulness (95.31%), followed by attractiveness (95.00%), indicating that students perceived COOLTRACE as beneficial for learning troubleshooting concepts while maintaining a high level of engagement. Likewise, the high ratings for ease of use, ease of learning, and efficiency suggest that the application can be operated independently with minimal technical difficulties. Overall, these findings demonstrate that COOLTRACE is practical for classroom implementation and effectively supports independent learning in refrigeration engineering.

The effectiveness of COOLTRACE was evaluated using a one-group pretest-posttest design involving 81 students enrolled in the Refrigeration Engineering course. Students completed the same troubleshooting test before and after using the developed learning medium. The descriptive statistics of students' pretest and posttest scores are presented in Table 6.

Table 6. Descriptive Statistics of Students' Troubleshooting Performance

Test	N	Mean	SD	Minimum	Maximum
Pretest	81	71.46	16.48	24	96
Posttest	81	96.69	6.13	64	100

As shown in Table 6, students' troubleshooting performance improved substantially after using the developed learning medium. The mean score increased from 71.46 on the pretest to 96.69 on the posttest, representing a considerable improvement in learning achievement. In addition, the posttest scores exhibited lower variability than the pretest scores, as reflected by the reduction in the standard deviation from 16.48 to 6.13. This finding indicates that students not only achieved higher troubleshooting performance but also demonstrated more consistent learning outcomes following the implementation of COOLTRACE. The effectiveness of the developed learning medium was further examined using the normalized gain (N-Gain), as presented in Table 7.

Table 7. N-Gain Analysis of Students' Troubleshooting Skills

Indicator	Result
Number of Students	81
Mean Pretest Score	71.46
Mean Posttest Score	96.69
Mean N-Gain	**0.84**
N-Gain Category	**High**
Students with High N-Gain	67 (82.7%)
Students with Moderate N-Gain	10 (12.3%)
Students with Low N-Gain	4 (4.9%)
Overall Conclusion	**Effective**

The normalized gain analysis further confirmed the effectiveness of the developed learning medium. As presented in Table 7, the mean N-Gain reached 0.84, which is classified as high according to Hake's criteria. Furthermore, 82.7% of the students achieved a high level of improvement, whereas only 4.9% remained in the low category. These findings indicate that the integration of authentic troubleshooting cases with structured Case-Based Learning activities effectively enhanced students' troubleshooting competence. The observed improvement reflects students' increased ability to identify fault symptoms, analyze possible causes, determine appropriate inspection procedures, evaluate alternative diagnoses, and select suitable corrective actions. Therefore, the developed digital learning medium can be considered effective in supporting the acquisition of troubleshooting skills in refrigeration engineering.

DISCUSSION

The development of COOLTRACE addressed the need for a learning environment that connects conceptual understanding with systematic troubleshooting practice in Refrigeration Engineering. Troubleshooting is not merely a matter of recalling technical information; rather, it requires learners to interpret fault symptoms, analyze possible causes, determine appropriate inspection procedures, and make diagnostic decisions based on incomplete or interrelated evidence. Such cognitive processes are difficult to develop through conventional instruction that primarily emphasizes theoretical explanations or procedural demonstrations. Therefore, Case-Based Learning (CBL) provides an appropriate instructional approach because it engages learners in authentic problem situations that require active analysis, evidence-based reasoning, and decision-making. One contribution of the present study is the integration of the entire troubleshooting cycle within a single web-based CBL environment. Instead of functioning solely as a repository of learning materials or an isolated simulation, COOLTRACE combines conceptual explanations, authentic troubleshooting cases, guided diagnosis, evaluation of alternative actions, corrective action sequencing, and formative feedback into a continuous learning process. This integrated structure enables students to progressively construct diagnostic reasoning while applying theoretical knowledge to practical troubleshooting situations. The findings support previous studies reporting that CBL promotes analytical thinking, problem-solving skills, and the application of theoretical knowledge in authentic learning environments (Agustin et al., 2023; Faiza & Wulandari, 2023; Mei & Azid, 2025). Likewise, Ali et al., (2024) demonstrated that systematically integrating CBL with digital learning environments strengthens critical thinking, while Sari & Khairunnisa (2025) emphasized that interactive case-based media improve learner engagement during problem-solving activities.

The expert validation results indicate that COOLTRACE successfully achieved coherence among learning objectives, technical content, Case-Based Learning activities, and media functionality. High validation scores suggest that the identified instructional needs were effectively translated into a structured digital learning product capable of supporting troubleshooting competency development. This finding is important because the quality of digital learning media depends not only on visual appearance or technical performance but also on the alignment between instructional objectives, learning activities, assessment, and the competencies to be developed. In COOLTRACE, refrigeration concepts, troubleshooting procedures, and diagnostic decision-making were intentionally organized into a coherent instructional sequence, ensuring that every learning activity contributed directly to the intended learning outcomes. These findings are consistent with Wiratmaja & Widayana (2023) and Hidayatullah et al., (2024), who reported that systematically developed digital learning media obtained high feasibility ratings when instructional content, problem-solving activities, and technical design were well aligned. Similarly, Ali et al., (2024) concluded that expert-validated CBL products provide a sound instructional foundation for vocational learning implementation.

The practicality findings further indicate that students were able to interact with COOLTRACE without substantial technical or navigational difficulties. The consistently high practicality scores suggest that learners perceived the application as intuitive, accessible, and supportive of independent learning. This positive response was likely influenced by the integration of conceptual materials, troubleshooting cases, diagnostic guidance, and feedback within a single learning environment, allowing students to complete learning activities without switching between multiple resources or platforms. Such an integrated design may reduce extraneous cognitive load, enabling learners to allocate greater cognitive resources to diagnostic reasoning rather than interface navigation or information searching. Furthermore, the sequential organization of learning activities provides instructional scaffolding that gradually guides students from conceptual understanding toward increasingly complex troubleshooting decisions. These characteristics help explain why students perceived the learning process as efficient and easy to follow despite the complexity of refrigeration fault diagnosis. Similar findings were reported by Al Husaeni et al. (2022), who found that web-based learning media integrating interactive resources and practice activities facilitated independent learning and generated positive student responses. Likewise, Putra & Ridoh (2021) emphasized that clear navigation structures and accessible user interfaces are essential factors contributing to the usability of web-based learning environments. Nevertheless, practicality should not be interpreted as evidence of instructional effectiveness by itself; rather, it demonstrates that the developed learning medium can be implemented successfully under realistic classroom conditions with minimal usability constraints.

The improvement in students' troubleshooting performance suggests that COOLTRACE effectively supported the cognitive processes required for diagnostic reasoning. Rather than memorizing component functions or standard operating procedures, students were repeatedly challenged to identify fault symptoms, analyze possible causes, evaluate alternative inspection strategies, and determine appropriate corrective actions within authentic case scenarios. This iterative reasoning process encouraged learners to integrate conceptual understanding with procedural knowledge, thereby promoting higher-order thinking skills essential for troubleshooting. The observed learning improvement therefore appears to have resulted not merely from exposure to digital media but from repeated opportunities to apply theoretical knowledge in structured problem-solving situations. This interpretation aligns with previous studies demonstrating that Case-Based Learning enhances analytical reasoning and problem-solving performance by engaging learners in contextual technical problems (Chankong et al., 2023; Gaspe & Dona, 2025). Likewise, Mei & Azid (2025) argued that CBL is particularly valuable in vocational education because it bridges abstract theoretical concepts with practical decision-making resembling real workplace situations.

Another factor that may have contributed to the observed improvement is the integration of guided diagnosis with immediate formative feedback throughout the learning process. During each troubleshooting activity, students received direct feedback regarding the appropriateness of their diagnostic decisions before progressing to subsequent stages. Consequently, incorrect responses became opportunities for reflection rather than simple indicators of failure. This iterative feedback mechanism resembles professional troubleshooting practice, where diagnostic hypotheses are continuously evaluated and refined as new evidence becomes available. By encouraging learners to reconsider the relationships among symptoms, possible causes, and corrective actions, the learning process fostered reflective thinking and strengthened diagnostic reasoning. Similar outcomes have been reported by Hidayatullah et al. (2024), who found that interactive simulations accompanied by immediate feedback significantly improved technical problem-solving performance. Likewise, Al Husaeni et al. (2022) demonstrated that web-based exercises incorporating response and correction features enabled students to monitor their understanding and repeatedly refine their learning. Accordingly, the effectiveness of COOLTRACE appears to result from the interaction between authentic case scenarios, structured reasoning activities, and formative feedback rather than from its web-based delivery alone.

Although the effectiveness results are encouraging, they should be interpreted as evidence of learning improvement following the intervention rather than definitive proof of a causal relationship. The one-group pretest-posttest design does not fully eliminate the influence of alternative explanations, such as students' prior knowledge, lecturer guidance during instruction, repeated exposure to similar assessment items, or concurrent learning experiences outside the intervention. Consequently, while the findings demonstrate that students' troubleshooting competence improved after using COOLTRACE, stronger causal conclusions require experimental or quasi-experimental studies involving appropriate comparison groups. Nevertheless, the consistently high practicality ratings, strong expert validation, and substantial learning gains collectively provide converging evidence supporting the educational potential of the developed learning medium.

The findings also provide important implications for vocational education and digital learning design. For lecturers, COOLTRACE offers a digital instructional environment that prepares students for laboratory-based troubleshooting by allowing them to practice diagnostic reasoning before interacting with actual refrigeration equipment. Such digital instructional scaffolding enables students to encounter diverse fault scenarios, evaluate diagnostic decisions, and receive immediate feedback without the limitations imposed by laboratory availability, equipment constraints, or instructional time. Consequently, laboratory sessions can be used more efficiently for developing practical measurement skills, equipment handling, and safety procedures rather than introducing basic diagnostic concepts. More broadly, the instructional framework developed in this study can be adapted to other vocational and engineering disciplines that require systematic diagnostic reasoning, including electrical maintenance, automotive engineering, industrial automation, and mechanical systems. Its transferable contribution lies not in the refrigeration content itself but in the integration of authentic problems, sequential diagnosis, evidence-based decision-making, and formative feedback within a coherent Case-Based Learning environment. This interpretation supports previous arguments by Fatokun & Gumbo (2024) regarding the importance of authentic problem-solving experiences in developing technical competence and by Mei & Azid (2025), who emphasized the contribution of CBL to critical thinking and workplace-oriented learning in vocational education.

CONCLUSION

This study successfully developed COOLTRACE, a web-based digital learning medium that integrates Case-Based Learning into a systematic refrigeration troubleshooting process. The product combines instructional materials, authentic failure cases, guided diagnosis, corrective action sequencing, and immediate feedback within a single learning environment. Expert evaluation confirmed that the developed media met the required instructional and technical standards, with overall validity scores of 97.50% from subject matter experts and 97.22% from media experts. Classroom implementation also demonstrated a very high level of practicality, with an overall score of 93.69%, indicating that students could access, understand, and operate the media with minimal difficulty.

The effectiveness evaluation showed an increase in the mean score from 71.46 on the pretest to 96.69 on the posttest. The mean N-Gain score of 0.8397 was classified as high, with 82.7% of students achieving a high-gain category. These findings indicate that COOLTRACE supported students in developing diagnostic knowledge and systematic decision-making related to refrigeration troubleshooting. Its main instructional contribution lies in organizing the complete troubleshooting cycle within an integrated case-based digital environment rather than presenting technical content or simulations separately. However, because the effectiveness test employed a one-group pretest–posttest design, the results should be interpreted as evidence of improvement following the intervention rather than definitive causal proof. Further research should examine COOLTRACE using comparison groups, broader refrigeration cases, multiple educational institutions, and performance-based assessments involving actual equipment or high-fidelity simulations to evaluate the retention and transfer of troubleshooting skills.

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ACKNOWLEDGEMENT

The authors would like to express their sincere gratitude to the Department of Electrical Engineering, Universitas Negeri Makassar, for supporting this research. The authors also thank the expert validators, lecturers, and students who participated in the validation, practicality, and effectiveness testing of the developed digital learning media.

AUTHOR CONTRIBUTION STATEMENT

KM conceived the study, developed the digital learning media, collected and analyzed the data, and drafted the manuscript. SY supervised the research, contributed to the research design, and critically reviewed the manuscript. MY validated the instructional content, contributed to data interpretation, and reviewed the final manuscript. All authors read and approved the final manuscript.

AI DISCLOSURE STATEMENT

The author used ChatGPT (OpenAI) during the preparation of this manuscript to assist with language editing, academic writing refinement, and improvement of grammar and readability. All generated content was critically reviewed, verified, and substantially revised by the author. The author takes full responsibility for the accuracy, originality, and integrity of the final manuscript.

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