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Mobile-Based Expert System for Fault Diagnosis of Air Handling Units

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Abstract*. This study aims to develop and evaluate an artificial intelligence–based expert system to support fault diagnosis in Air Handling Units (AHUs). Early fault identification in AHU systems is often constrained by reliance on technician experience, which may lead to inconsistent diagnostic outcomes. The proposed system is intended to provide a consistent, explainable, and practical decision-support tool to assist maintenance personnel, particularly less-experienced technicians, in identifying AHU faults accurately. The research adopts a rule-based expert system approach using forward chaining inference. Knowledge acquisition was conducted through structured interviews with experienced HVAC technicians and supported by technical documentation. The resulting knowledge base consists of observable symptoms, diagnostic rules, and corresponding corrective actions. The system was implemented as an Android-based mobile application to enable direct field usage. System validation was performed using real operational fault scenarios, with expert diagnoses serving as the reference standard. Evaluation results indicate full agreement between the system-generated diagnoses and expert assessments across all tested scenarios. This demonstrates that the proposed system is capable of producing accurate and consistent diagnostic outcomes within its defined knowledge domain. The system operates using deterministic rules without incorporating uncertainty modeling or probabilistic reasoning. Additionally, validation was limited to a finite number of real-world scenarios, which may affect generalizability to broader AHU configurations. The expert system can be utilized as a practical diagnostic aid in routine AHU maintenance, improving response time, diagnostic consistency, and technician training effectiveness. This study contributes a mobile-based, explainable expert system specifically tailored for AHU fault diagnosis, emphasizing practical deployment and rule transparency rather than data-intensive learning models.*

Keywords: *Expert System; Forward Chaining; Air Handling Unit; Fault Diagnosis; Artificial Intelligence*

INTRODUCTION

Heating, Ventilation, and Air Conditioning (HVAC) systems play a critical role in maintaining indoor environmental quality, energy efficiency, and occupant comfort in modern buildings (Sugarman, 2024). Within HVAC installations, the Air Handling Unit (AHU) functions as a central component responsible for regulating airflow, temperature, humidity, and air cleanliness (Hussain et al., 2020). Any malfunction occurring at the

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AHU level may propagate through the entire HVAC system, leading to reduced thermal comfort, increased energy consumption, and higher operational costs (Andersen et al., 2024; Rafati et al., 2022). Consequently, effective fault diagnosis in AHU systems is essential to ensure reliable building operation and sustainable facility management (Chen et al., 2023; Sinopoli, 2010).

Despite the importance of AHU reliability, fault diagnosis in practice remains largely dependent on manual inspection and technician experience (Saran et al., 2020). This reliance introduces several challenges, including subjective decision-making, inconsistent diagnostic outcomes, and extended response times, particularly when performed by less-experienced technicians (Leong, 2019). As AHU systems become more complex due to increasing automation and performance requirements, conventional diagnostic approaches struggle to keep pace with operational demands (Balasubramaniam, 2021). These challenges highlight the need for intelligent diagnostic tools capable of supporting maintenance personnel with structured and systematic decision-making.

Artificial intelligence (AI) has been widely explored as a means of enhancing fault detection and diagnosis in HVAC systems (Al-Aomar et al., 2024; Alnuman et al., 2023; Balasubramaniam, 2021). Data-driven approaches such as machine learning and neural networks have demonstrated promising performance in identifying complex fault patterns (Al-Aomar et al., 2024). However, these methods often require large volumes of high-quality historical data, substantial computational resources, and sophisticated model tuning (Leong, 2019). In many real-world building environments, especially in developing regions or legacy facilities, such data availability and infrastructure are limited (Hussain et al., 2020; Sánchez-Barroso & Sanz-Calcedo, 2019). Moreover, black-box characteristics of learning-based models can hinder interpretability, making it difficult for technicians to understand or trust the diagnostic outcomes (Kabir et al., 2025; Wang et al., 2025).

In contrast, rule-based expert systems offer an alternative AI paradigm that emphasizes transparency, explainability, and domain knowledge representation (Balasubramaniam, 2021; Fang et al., 2022). By encoding expert knowledge in the form of logical rules, expert systems can replicate human diagnostic reasoning while maintaining consistency across cases (Munir et al., 2024; Rich & Knight, 1991; Suyanto, 2014). Forward chaining inference, in particular, is well suited for diagnostic applications, as it derives conclusions directly from observed symptoms, mirroring the workflow commonly employed by maintenance technicians during troubleshooting processes (Al Hakim et al., 2022; Chani, 2022; Yantoro & Astuti, 2022; Yunita et al., 2020).

Previous studies have applied expert systems and hybrid AI techniques to HVAC fault diagnosis; however, many focus on specific subsystems, require high computational capacity, or lack practical deployment considerations (Al-Aomar et al., 2024; Alnuman et al., 2023; Chen et al., 2023; Fang et al., 2022; Wang et al., 2025). Furthermore, few studies emphasize mobile-based implementations that enable real-time field usage by technicians (Zhou et al., 2023). This gap suggests an opportunity to develop an expert system that balances diagnostic accuracy, explainability, and practical usability without reliance on extensive datasets or complex computational infrastructure.

Therefore, this study proposes a rule-based expert system employing forward chaining inference for AHU fault diagnosis, implemented as an Android-based mobile application. The system is designed to assist technicians in identifying AHU faults based on observable symptoms and to provide corresponding corrective recommendations. By validating the system using real operational scenarios and expert judgment, this research aims to demonstrate that a lightweight, explainable AI approach can effectively support AHU maintenance activities. The contribution of this work lies in its practical orientation, focusing on deployability, diagnostic consistency, and decision-support value in real-world HVAC operations.

METHODS

This study employed a research and development approach to design, implement, and validate a rule-based expert system for diagnosing faults in Air Handling Units (AHUs). The methodological framework focused on systematic knowledge acquisition, structured rule formulation, and empirical validation using real operational scenarios. The overall process was designed to ensure diagnostic transparency, reproducibility, and practical applicability in field maintenance environments. The following Figure 1 shows the research flowchart.

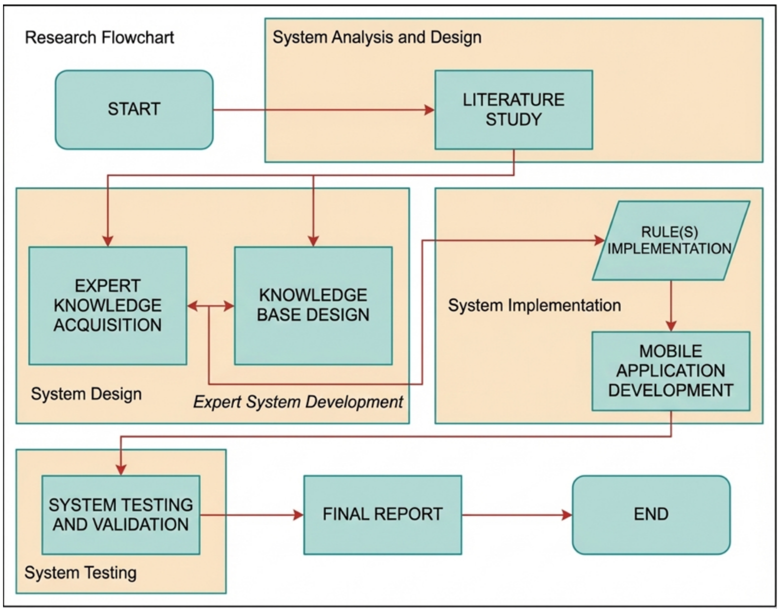

Figure 1. Flowchart diagram of this study.

Knowledge Acquisition and Problem Definition

Knowledge acquisition was conducted through structured interviews and consultations with experienced HVAC technicians responsible for AHU maintenance in a commercial building environment. The objective was to identify recurrent fault types, observable symptoms, diagnostic reasoning patterns, and standard corrective actions (Camejo, 1989). Expert knowledge was complemented by a review of technical manuals and HVAC maintenance documentation to ensure consistency with established operational practices (O'Keefe & O'Leary, 1993; Sugarman, 2020). The diagnostic problem was defined as the identification of AHU faults based on combinations of observable symptoms encountered during routine inspection.

Knowledge Base Construction

The acquired knowledge was formalized into a rule-based knowledge base consisting of three components: symptoms, diagnostic rules, and corrective actions, all of them also categorize as codes, respectively. Observable symptoms were encoded as discrete facts representing measurable or perceivable AHU conditions, such as abnormal airflow, excessive noise, or temperature deviations. Diagnostic rules were formulated using an IF–THEN structure, mapping specific combinations of symptoms to corresponding fault categories. Each diagnostic outcome was linked to a predefined corrective recommendation to support maintenance decision-making.

Inference Mechanism

The expert system employed a forward chaining inference mechanism to derive diagnostic conclusions. Forward chaining initiates reasoning from user-provided facts and iteratively matches them against the rule base until a valid diagnosis is inferred. This approach reflects the natural troubleshooting process used by technicians, enabling intuitive interaction and transparent reasoning. The inference process was deterministic, producing a diagnosis only when all conditions of a rule were satisfied.

System Implementation

The expert system was implemented as a mobile application on the Android platform to facilitate field deployment. The user interface allowed technicians to select observed symptoms through a structured input form. Upon submission, the inference engine processed the input and generated diagnostic results along with corrective recommendations. The system architecture was designed to allow future expansion of rules and symptoms without modifying the inference mechanism.

System Validation

System validation was performed using real AHU fault scenarios encountered during operational maintenance. Diagnostic results generated by the system were compared with expert technician assessments to evaluate accuracy and consistency. The validation process focused on assessing diagnostic correctness rather than predictive performance, aligning with the system's rule-based design philosophy.

RESULTS

The developed expert system was evaluated to assess its diagnostic performance, consistency with expert judgment, and operational feasibility in real maintenance scenarios. The results are presented by focusing on system behavior, diagnostic accuracy, and validation outcomes rather than implementation details.

Expert System Diagnostic Performance

The expert system processed observable AHU symptoms as factual inputs and generated diagnostic conclusions using forward chaining inference. Across all evaluated scenarios, the system successfully matched symptom combinations to predefined diagnostic rules and produced corresponding fault classifications and corrective recommendations. The inference process terminated deterministically, ensuring that a diagnosis was generated only when all rule conditions were fully satisfied.

A summary of the diagnostic outcomes was visualized using a comparison Figure 2 illustrating system-generated diagnoses versus expert technician diagnoses across ten real-world fault scenarios (system trials using Indonesian language). Each scenario demonstrated exact agreement between the system output and expert judgment, indicating consistent diagnostic reasoning within the defined knowledge domain.

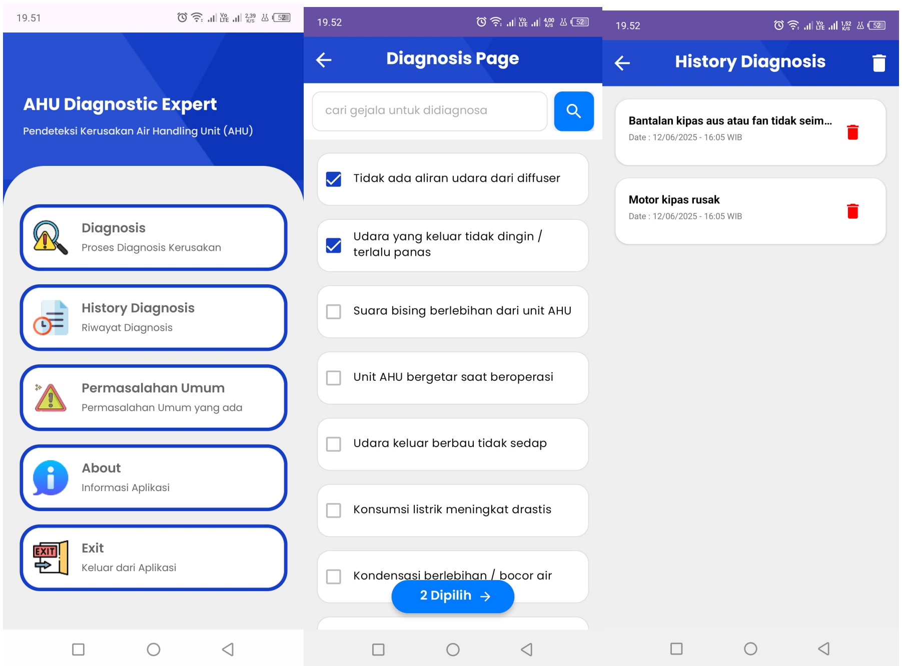

Figure 2. Comparison of the system's diagnose

Validation Against Expert Assessment

System validation involved ten operational AHU fault cases representing commonly encountered maintenance issues, including airflow disruption, abnormal noise, temperature deviation, and drainage problems (see Figure 3). For each case, diagnoses produced by the expert system were independently evaluated by senior HVAC technicians. The results showed complete concordance between the two diagnostic sources. This outcome confirms that the encoded rules accurately captured expert reasoning patterns for the selected fault categories.

Figure 3. Documentation of system validation in real-world.

To illustrate validation results, a categorical agreement figure was used to depict the proportion of matching diagnoses between the system and experts. The visualization indicated a 100% agreement rate across all evaluated cases, reflecting high internal validity of the rule base.

Diagnostic Accuracy Measurement

Diagnostic accuracy was quantified using a direct agreement-based metric, as the system operates under deterministic rule-based logic rather than probabilistic classification. Since no discrepancies were observed between system outputs and expert diagnoses, the calculated diagnostic error was zero across all test cases. Consequently, the system achieved a diagnostic accuracy of 100% within the scope of the evaluation dataset.

Furthermore, Figure 4 shows the mapping graph of symptom diagnosis, as well as Figure 5 shows the Bipartite Network Graph (BNG) visualizes the relationships between the input symptoms (Left) and the resulting diagnoses (Right). This type of figure is often preferred in journal manuscripts over simple tables because it clearly illustrates the complexity and connectivity of the expert system's rules (e.g., how G01 is a common symptom across multiple different diagnoses). This result demonstrates that, for the predefined symptom–rule mappings, the expert system reliably reproduces expert-level diagnostic conclusions without ambiguity.

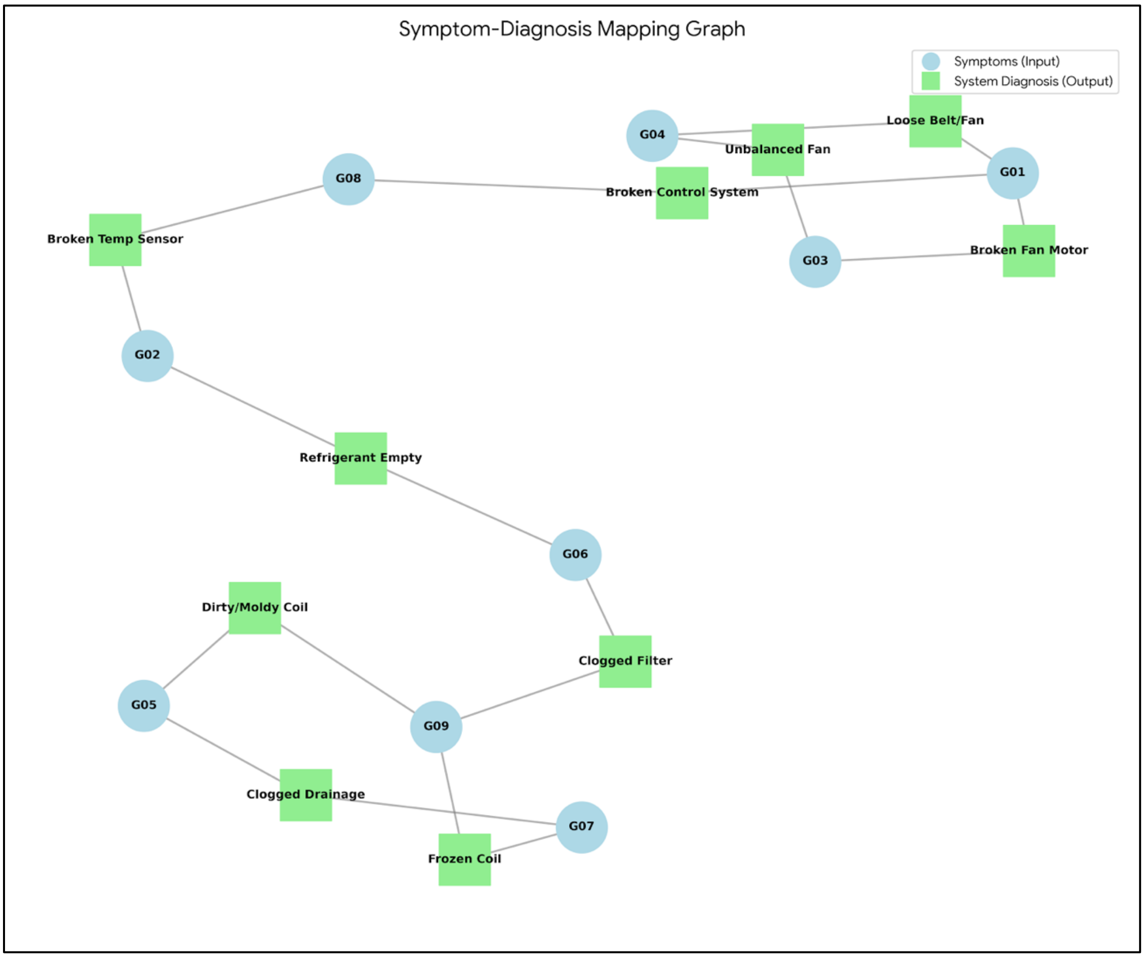

Figure 4. Symptom-diagnosis mapping graph

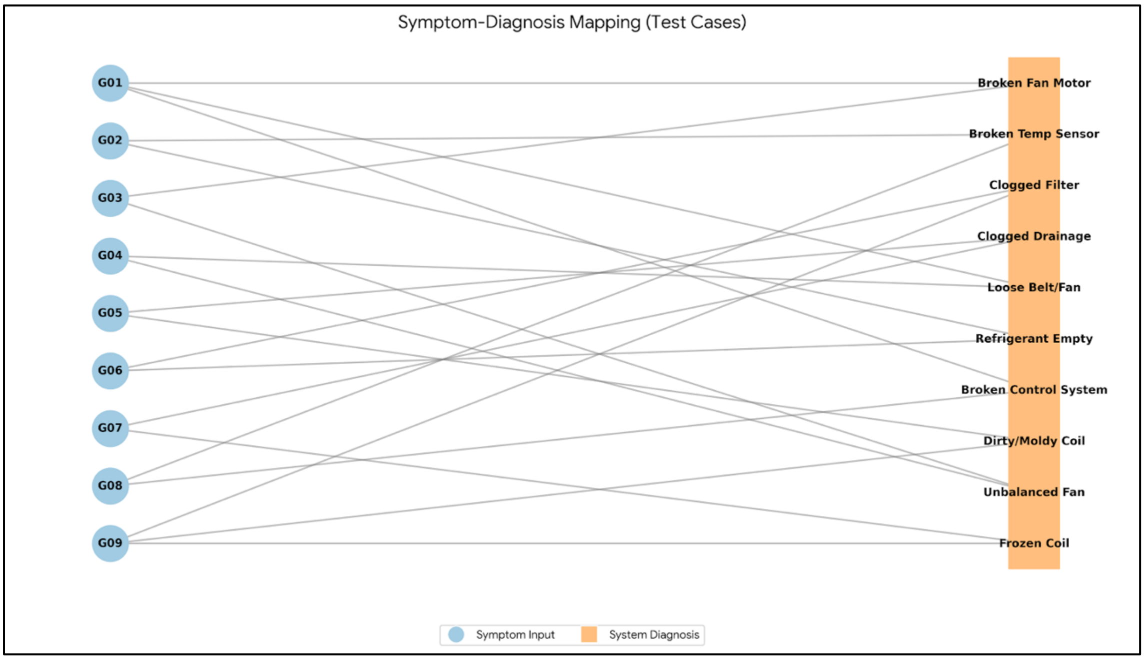

Figure 5. Bipartite graph visualization of the expert system validation results. The graph maps the relationships between input symptom sets (G01–G09) and the corresponding diagnoses. All 10 mapped cases shown were validated as accurate by the human expert (100% agreement rate).

Operational Feasibility and User Evaluation

In addition to diagnostic correctness, the system was evaluated for operational feasibility through field usage by junior technicians, it can be seen in Figure 6. User feedback was summarized using a usability evaluation figure, indicating that the majority of users found the system intuitive and helpful for guiding diagnostic decisions. Most respondents reported that the system reduced uncertainty during fault identification and improved their understanding of AHU malfunction causes.

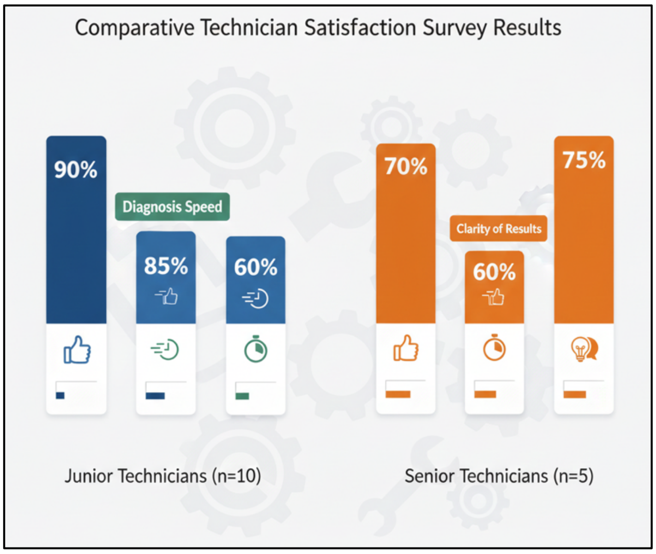

Figure 6. Results from the junior technician satisfaction survey (n=10) regarding the developed expert system application. The survey assessed ease of use, diagnosis speed, and clarity of recommendation results. High satisfaction rates (90% for ease of use, 85% for diagnosis speed, and 80% for clarity) indicate strong user acceptance and real-world applicability of the system.

DISCUSSION

The results of this study demonstrate that a rule-based expert system using forward chaining inference can effectively support fault diagnosis in Air Handling Units (AHUs) within real operational environments. The complete agreement between system-generated diagnoses and expert technician assessments across all evaluated scenarios indicates that the encoded rules successfully captured domain-specific diagnostic reasoning. This finding reinforces the suitability of knowledge-driven artificial intelligence approaches for HVAC maintenance tasks, particularly in contexts where data availability and computational resources are limited.

The diagnostic performance observed in this study is consistent with earlier research that applied artificial intelligence techniques to AHU fault detection and diagnosis. For instance, previous work employing machine learning models, such as Support Vector Machines and Neural Networks, demonstrated high diagnostic accuracy for specific AHU subsystems, particularly in heat recovery components (Alnuman et al., 2023; Balasubramaniam, 2021; Madhikermi et al., 2019; Palermo et al., 2023). However, such approaches often require large datasets and involve complex model training processes (Zhou et al., 2023). In contrast, the present study achieved comparable diagnostic accuracy using a deterministic rule-based framework, highlighting that high diagnostic reliability does not necessarily require data-intensive learning algorithms when expert knowledge is well structured.

Studies utilizing explainable artificial intelligence (XAI) for AHU fault diagnosis emphasize transparency and interpretability, allowing engineers to understand how diagnostic decisions are derived (Meas et al., 2022). The expert system developed in this research aligns with these principles by offering fully explainable reasoning through explicit IF–THEN rules. Unlike XAI models that still rely on high computational capacity and complex model architectures (Madhikermi et al., 2019), the proposed system achieves explainability through simple logical inference, making it more accessible for practical deployment in routine maintenance environments.

Comparative insights can also be drawn from decision tree–based diagnostic systems previously applied to AHU fault detection (Balasubramaniam, 2021). While decision tree models have shown potential in mapping technician knowledge to diagnostic rules, some studies reported limitations related to rule validity under specific operational conditions. The deterministic nature of the rule base in this study, validated directly through expert consultation and field testing, reduces such variability by restricting inference to explicitly verified symptom combinations. This approach enhances diagnostic consistency, particularly for frequently occurring fault types.

The mobile-based implementation of the expert system represents an additional contribution when compared to prior research that primarily focused on desktop or server-based diagnostic tools (Bergam et al., 2020). Mobile accessibility enables technicians to perform diagnosis directly at the equipment location, reducing reliance on external documentation or senior personnel (Storey et al., 2025). User feedback from junior technicians further supports the practical value of this design choice, as most users reported improved confidence and reduced diagnostic uncertainty.

Although the system demonstrated perfect agreement with expert diagnoses within the evaluation scope, its deterministic rule-based design also introduces certain limitations. The system does not currently account for uncertainty, partial symptom manifestation, or overlapping fault conditions, which are common in complex HVAC systems. This limitation mirrors observations in earlier expert system studies, where rule-based inference performs best within clearly defined operational boundaries.

Nevertheless, such constraints are acceptable for early-stage diagnosis and routine maintenance support, particularly when the goal is decision assistance rather than autonomous fault prediction.

Overall, the findings of this study confirm that a rule-based expert system with forward chaining inference can serve as an effective, interpretable, and practical diagnostic tool for AHU maintenance. When compared with data-driven and hybrid AI approaches reported in the literature, the proposed system offers a balanced trade-off between accuracy, explainability, and deployment feasibility. This positions the system as a complementary solution within the broader landscape of intelligent HVAC maintenance technologies.

CONCLUSION

This study successfully developed and evaluated a rule-based expert system employing forward chaining inference to support fault diagnosis in Air Handling Units (AHUs). By formalizing expert technician knowledge into a structured rule base and implementing the system as a mobile application, the proposed approach demonstrated accurate and consistent diagnostic performance across all evaluated real-world scenarios. The complete agreement between system outputs and expert assessments confirms that the system effectively replicates expert-level diagnostic reasoning within its defined scope. These findings indicate that an explainable, lightweight artificial intelligence approach can provide practical decision support for AHU maintenance activities, particularly in environments with limited data availability and varying technician expertise, while maintaining transparency and ease of deployment.

LIMITATION

Despite its demonstrated effectiveness, this study has several limitations that should be acknowledged. First, the expert system operates using deterministic rule-based inference and does not incorporate uncertainty modeling, such as probabilistic reasoning or confidence weighting. As a result, the system may be less effective when symptoms are ambiguous, incomplete, or overlapping across multiple fault conditions.

Second, system validation was conducted using a limited number of real-world fault scenarios within a specific operational context. While the results indicate high internal validity, broader validation across diverse AHU configurations, operating conditions, and building types is necessary to assess generalizability.

Finally, the system relies on manually selected symptoms provided by users, which introduces dependency on correct symptom observation. Future work may address these limitations by integrating real-time sensor data, uncertainty handling techniques, or hybrid approaches combining rule-based reasoning with data-driven models.

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