



INTERNATIONAL JOURNAL OF
INNOVATION AND
INDUSTRIAL REVOLUTION
(IJIREV)

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SMART CONTROL WITH FUZZY LOGIC: A MULTI-APPLICATION FIS-BASED COMPARATIVE ANALYSIS


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Article Info:

Article history:

Received date: 23.04.2026

Revised date: 18.05.2026

Accepted date: 01.06.2026

Published date: 22.06.2026

To cite this document:

Najib, N. M., Awang, N. A., & Sufter, N. S. (2026). Smart Control with Fuzzy Logic: A Multi-Application Fis-Based Comparative Analysis. *International Journal of Innovation and Industrial Revolution*, 8(25), 227-240.

Abstract:

Fuzzy logic controllers (FLCs) have proven applicable in a wide range of smart control applications by handling imprecision, uncertainties and mimicking human reasoning. This paper presents a comparative study of FIS-based projects in diverse domains of smart controller which includes air-conditioning, washing machine, an irrigation system, and traffic-light. The system uses linguistic inputs and produces control outputs. All systems employ Mamdani-Fuzzy inference system type with triangular and trapezoidal membership functions. The rule bases on the order of 27 to 81 rules. This study summarizes each project based on inputs, outputs, membership functions, rule evaluation, and defuzzification method and the compare their performance in the term of responsiveness, service efficiency, and resource usage. Results indicate that fuzzy controllers can significantly improve efficiency and adaptively tuning control actions. The findings and analysis highlight the common design patterns of fuzzification process and its challenges for rule explosion involving many inputs. A generalized FIS framework and methodology framework was introduced to illustrate the collective architecture as a guideline in future endeavours. This synthesis not only demonstrates the versatility of fuzzy logic in automation and resource management but also serves as a reference survey of FIS design. The paper concludes with some limitations for further optimization in adaptive neural or Sugeno extensions and suggests best practices for implementing fuzzy controllers in design automation.

DOI: 10.35631/IJIREV.825013

Keyword:

Fuzzy Controller, Fuzzy Inference System, Fuzzy Logic, Mamdani Fuzzy Logic, Smart Control



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Introduction

Fuzzy logic enables control systems to handle uncertainty and approximate human decision-making (Pagare et al., 2025; Tunc et al., 2021). It has been widely applied to smart control problems in consumer appliances, HVAC, agriculture, and traffic engineering. For example, recent studies show fuzzy controllers can reduce energy use in air conditioners by 20–25% compared to fixed controllers (Pagare et al., 2025) and adapt traffic signals to changing density to cut waiting times (Tunc et al., 2021). At the heart of this shift is fuzzy logic, a mathematical framework that permits the representation of uncertainty and imprecision in a manner that closely approximates human cognition. Traditional control methodologies, most notably the Proportional-Integral-Derivative controller, rely on the availability of a precise mathematical model of the plant. However, in real-world applications such as climate control, traffic management, and precision agriculture, the dynamics of the system are often non-linear, time-varying, and subject to stochastic environmental disturbances (Nazha et al., 2025). Fuzzy logic addresses these challenges by allowing for "computing with words," where linguistic variables replace numerical values, enabling the integration of expert human knowledge into the control loop. A fuzzy logic controller (FLC) operates on the principle of fuzzy sets, where membership is not a binary state of belonging or not belonging, but rather a continuous degree of truth ranging from 0 to 1 (De Souza, 2023). This flexibility is essential for handling the vagueness inherent in sensory data, such as determining whether a room is "warm" or "very warm."

The FLC maps crisp sensor inputs to control outputs via linguistic rules. A fuzzy inference system (FIS) has four main blocks (Negnevitsky, 2005). The first block is fuzzification which transforms crisp inputs into linguistic fuzzy sets, next is knowledge base which comprises a rule base of IF-THEN rules and a database of membership function. The third block is inference engine where the engine applies fuzzy reasoning to derive output fuzzy sets, and the last block is defuzzification converting fuzzy outputs to crisp control actions. The common approaches of fuzzy consequents use Mamdani FIS, and the crisp-output function applied the concept of Takagi–Sugeno FIS. In control applications, Mamdani FIS with triangular or trapezoidal membership functions (MFs) is popular due to interpretability. This interpretability is further enhanced by defining input ranges through intuitive linguistic variables such as low, medium, or high which allow for the implementation of expert-derived heuristics. For instance, the IF-THEN rules are formed as "IF temperature is High AND humidity is Low THEN fan speed is Fast". The key design choices include MFs shape or overlap, rule evaluation, and defuzzification method which the centroid or Centre of Gravity (COG) is most common applied. Through these stages, a crisp input from a sensor is transformed into a fuzzy value,

processed according to a set of IF-THEN rules, and then converted back into a crisp control signal for an actuator (Silvestri et al., 2025).

The advantage of FIS is incorporating expert reasoning and smoothly handling nonlinearities (Neugebauer et al., 2023). For example, fuzzy washing machine controllers adjust wash time and water use based on sensed dirt level, saving both water and energy, while fuzzy irrigation systems use soil moisture and weather inputs to optimize watering schedules (Neugebauer et al., 2023). In traffic control, FIS adapts green-phase durations to real-time queues, improving flow (Tunc et al., 2021). While FIS have proven highly effective in smart control, limited comprehensive comparative analyses of the design architectures across multiple domains. Consequently, this situation leads to lack of understanding regarding common design practices, implementation challenges, and development frameworks that could simplify future applications. To bridge this gap, this study systematically compares six fuzzy logic-based smart control systems (application in air conditioning, washing machines, irrigation, traffic lights). A generalized FIS framework and methodology derived from their shared characteristics in the term of the identify common structures of inputs, rules, outputs, performance benefits, and lessons learned of the FLC and shows how each case defines linguistic variables, constructs MFs and rules, and evaluates outcomes. The key contribution is a structured comparison that highlights fuzzy logic's flexibility across domains and offer insights a reference model for future system development.

The rest of the paper is organized as follows: Section 2 reviews background study of FIS-Based selected domain, Section 3 outlines the comparative methodology, Section 4 summarizes each control application, Section 5 concludes the study.

Literature Review

This section will discuss the main four domain of FIS-based projects in FLC.

Smart Air Conditioner Control System

Many existing an air conditioning system still rely on basic ON/OFF controls or fixed temperature settings, which resulting in inconsistent temperature as the traditional system cannot adapt to environmental changes or occupancy levels (Isikdemir et al., 2022). Besides, some of important factors affecting thermal comfort, such as humidity, temperature variation, and occupancy density, are often overlooked, leading to uneven comfort and unnecessary energy consumption (Taleb et al., 2023). The previous studies have demonstrated that fuzzy logic is effective in handling uncertainty and imprecise environmental data in HVAC systems by intelligently adjusting cooling settings to improve thermal comfort while reducing energy consumption (Pagare et al., 2025) and automatically regulate indoor temperature based on environmental conditions and occupancy levels (Manimozhi et al., 2025).

Traffic Light Control System

Traffic light control systems are important to help reduce accidents and traffic congestion by controlling which direction receives the green light and organizing traffic movement systematically (Idris et al., 2024). The system was also improved with electricity, making traffic control safer and more reliable (Idris et al., 2024). Since then, traffic light systems have evolved with timers, sensors, and computer technologies to improve traffic management efficiency

(Hartanti et al., 2019). However, many traffic light systems in Malaysia still use conventional fixed-timer methods where signal timings remain constant and cannot adapt to actual traffic conditions, causing unnecessary delays and congestion (Fahrnisa et al., 2024; Abas & Jefrydin, 2023).

Smart Irrigation System

Traditional irrigation methods, such as flooding fields or using fixed-schedule sprinklers, often waste water or fail to provide enough moisture because it cannot adapt to actual soil and weather conditions. Therefore, modern smart irrigation systems are needed to improve irrigation efficiency. For example, fuzzy logic-based irrigation controllers can automatically adjust water pump output using real-time environmental data, helping to prevent over-irrigation and under-irrigation while reducing water and energy consumption (Bukhari et al., 2024). In addition, smart irrigation systems integrated with IoT, wireless communication, and automated decision-making can improve crop yields, reduce operational costs, and ensure efficient use of water resources by supplying water based on actual crop needs instead of fixed schedules (Krishnan et al., 2020).

Smart Washing Machine

Most conventional washing machines use fixed settings that cannot adapt to different washing conditions and often waste time, water, and electricity, making them less efficient and more costly to operate (Salau & Takele, 2022). To overcome these problems, the smart washing machine fuzzy system applies fuzzy logic to create an intelligent control system that automatically adjusts washing conditions based on fabric type, load size, and dirt level (Salau & Takele, 2022). Compared to traditional PID controllers, FLC are more flexible in handling uncertain or incomplete data and can imitate human decision-making through “degrees of truth” (Zheng et al., 2022). This approach improves washing accuracy and efficiency while reducing water and energy consumption, making washing machines more intelligent and environmentally friendly (Kareem & Ali, 2021).

Methodology of Comparative Analysis

This section describes the comparative analysis methodology used to evaluate FIS-based projects. The analysis focuses on extracting the main components of each FIS implementation, enabling systematic comparison across different controller applications. The selected systems were developed as undergraduate project assignments and implemented using MATLAB Fuzzy Logic Toolbox with simulation-based testing environments. These projects were chosen due to their similarity of using FIS while addressing different intelligent control problems. The Figure 1 illustrated the comparative analysis conducted based on the following criteria:

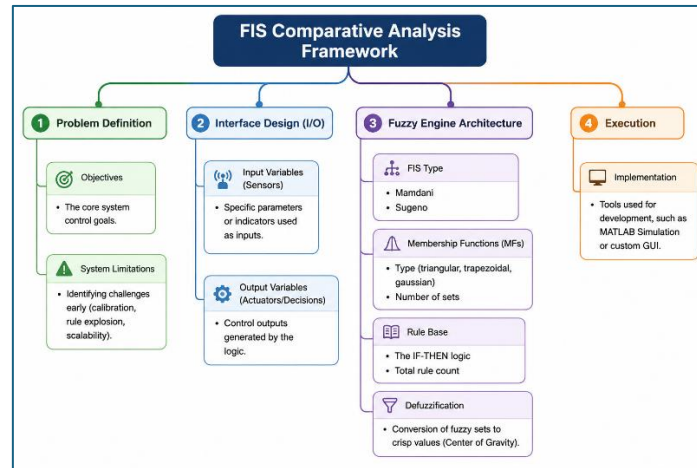


Figure 1: A Framework of FIS Comparative Analysis

Source: The image was generated with the assistance using ChatGPT based on conceptual designs provided by the authors.

Data for this study was collected from project reports, system documentation, fuzzy rule bases, and designs, and graphical user interface (GUI) implementations. The extracted criteria from each project were comparatively analyzed to identify similarities, differences, and implementation trends among the FLC. A comparative summary will be highlighting the system inputs, outputs, MFs designs, and implementation characteristics of each project and identified limitations. This comparative framework provides a structured overview of how FLC can be adapted across multiple smart control applications whereas effectively handling uncertainty and imprecise system conditions.

FIS-based Case Study

This section will briefly be summarized each project's objectives, FIS engine and its implementation, and then highlighted the smart control behaviour. The selected projects employed the Mamdani fuzzy inference system due to its intuitive rule-based structure and strong interpretability for control applications. In contrast, Sugeno FIS typically uses mathematical functions in the consequent part, resulting in easier optimization. However, Mamdani FIS was preferred in the selected study conducted by the undergraduates because the primary objective was adaptive control rather than mathematical optimization.

Intelligent Air Conditioner Temperature Control System (I-ACTCS) (Faizol et al., 2025):

The objective of this project is to develop an intelligent air conditioning system that can automatically adapt to changes in atmospheric temperature conditions. The system uses a Mamdani-type to control the air conditioner temperature level, with outputs categorized as *Cold*, *Slightly Cold*, *Neutral*, and *Warm*. The fuzzy model applies triangular and trapezoidal MFs with three fuzzy sets for each input variable, namely *Inside Temperature (Low, Medium, High)*, *Temperature Difference* between indoor and outdoor environments (*Low, Medium, High*), *Dew Point Temperature (Comfortable, Humid, Uncomfortable)*, and *Occupancy Percentage (Low, Medium, High)*. A total of 81 IF-THEN rules were developed for the control process. The defuzzification process uses the COG method. The system was implemented using MATLAB simulation and demonstrated the ability to continuously adapt cooling conditions.

However, the system requires proper tuning of MFs to improve robustness and system performance.

Smart Washing Machine (Hamdan et al., 2025):

The objective of this project is to optimal washing settings to achieve energy consumption at its most efficient level. The system uses a Mamdani-type to control the wash time (*Short, Medium, Long*), water level (*Low, Medium, High*) and spin speed (*Slow, Medium, Fast*). The fuzzy model applies triangular MFs with three fuzzy sets for each input variable, namely *Dirt Level (Low, Medium, High)*, *Load Size (Small, Medium, Large)*, and *Fabric Type (Delicate, Normal, Coarse)*. A total of 27 IF–THEN rules were developed for the control process. The defuzzification process uses the COG method. The system was implemented using MATLAB simulation and demonstrated the ability to improves wash efficiency, reduces water and energy use by tailoring cycle to actual need. However, the system requires accurate sensing of dirt or fabric as it can be tricky and rule design may expand with more specified input.

Smart Irrigation System using Fuzzy Logic (Noramli et al., 2025):

The objective of this project is to design a system that controls water flow according to temperature, light intensity, and soil moisture. The system uses a Mamdani-type to control the duration (in seconds), with outputs categorized as *Short, Medium, and Long*. The fuzzy model applies triangular and trapezoidal MFs with three fuzzy sets for each input variable, namely *Soil Moisture (Dry, Normal, Wet)*, *Temperature (Cold, Normal, Hot)*, and *Light Intensity, (Dim, Normal, Bright)*. A total of 27 IF–THEN rules were developed for the control process. The defuzzification process uses the COG method. The system was implemented using MATLAB simulation and demonstrated the system works intelligently. However, the system requires proper sensor calibration.

Smart Traffic Light (Jasni et al., 2025):

The objective of this project is to develop an adaptive traffic light control system using fuzzy logic that can adjust green light duration based on actual traffic conditions such as vehicle density and queue length. The system uses a Mamdani-type to control the green light duration, with outputs categorized as *Very Short, Short, Medium, Long and Very Long*. The fuzzy model applies triangular and trapezoidal MFs with three fuzzy sets for each input variable, namely *Number of Vehicles (Few, Normal, Many)*, *Queue Length (Short, Normal, Long)*, and *Number of Lanes, (Few, Normal, Many)*. A total of 27 IF–THEN rules were developed for the control process. The defuzzification process uses the COG method. The system was implemented using MATLAB simulation and demonstrated the system successfully. However, the system requires to tune some input to optimal the green light duration.

Fuzzy Logic Application in Smart Air Conditioners Control Systems (Fakhrol Ruzi et al., 2025):

The objective of this project is to optimize the workload of the compressor by implementing a variable speed strategy rather than operating in fixed cycles (a case in Cameron Highland). The system uses a Mamdani-type to control the compressor speed, with outputs categorized as *Stop, Slow, Medium, and Fast*. The fuzzy model applies triangular and trapezoidal MFs with three fuzzy sets for each input variable, namely *Inside Temperature (Cold, Comfort, Warm)*, *Relative*

Humidity (Dry, Optimal, Humidity), and Room Size (Small, Medium, Large). A total of 27 IF–THEN rules were developed for the control process. The defuzzification process uses the COG method. The system was implemented using MATLAB simulation and demonstrated the ability to works well in different conditions like cool with dry rooms until hot with high humid large spaces. However, the system requires proper clarification on selected of inputs and output tuning to improve system performance especially in low temperature area.

Fuzzy Logic in Traffic Light Control System (Shahrul Fadhel et al., 2025):

The objective of this project is to implement a dynamic traffic signal control system that optimizes green light duration. The system uses a Mamdani-type to control the green light duration, with outputs categorized as *Short, Medium, and Long*. The fuzzy model applies triangular and trapezoidal MFs with three fuzzy sets for each input variable, namely *Number of Waiting Cars (Low, Medium, High), Fog Level (Clear, Medium, Heavy), and Time of Day (Morning, Lunch, Evening)*. A total of 27 IF–THEN rules were developed for the control process. The defuzzification process uses the COG method. The system was implemented using MATLAB simulation and demonstrated that fuzzy logic controller responds effectively to real-world traffic and environmental conditions. However, the system did not address the limited input roughness and inefficient timing during the hours that fall between the defined sets.

In fuzzification process, the crisp input values are converted into fuzzy values using predefined membership functions. The membership degree of a fuzzy value belongs to [0,1]. Then, the inference engine generates the fuzzy output using rule evaluation and IF-THEN rules. The defuzzification process were converting back the fuzzy values into crisp values using COG method (refer Eq. 1):

$$COG = \frac{\int x\mu(x) dx}{\int \mu(x) dx} \quad (1)$$

Where $\mu(x)$ is represented the aggregated output membership and x is represented input variable.

Comparative Analysis

Table 1 summarizes the core characteristics of each project, including the system objectives, input and output variables, MFs design, rule evaluation, and executed MATLAB-based simulations with graphical user interface (GUI) support to evaluate system behaviour under different input conditions. The analysis shows that all projects utilized Mamdani-type FIS due to its appropriateness for human-like reasoning and intuitive rule-based control. The COG method was consistently applied for the defuzzification process to convert fuzzy outputs into crisp control decisions. Most projects employed triangular and trapezoidal MFs because of simplicity and feasibility of in MATLAB implementation environments.

Table 1: Comparative Summary of Fuzzy Logic-Based Smart Control Systems

Project & Objectives	I/O Variables	Fuzzy Engine Architecture	Execution	Limitations
Intelligent Air Conditioner Temperature Control System (I-	Input: Temperature, Temperature Difference,	<ul style="list-style-type: none"> • Mamdani • Triangular & Trapezoidal MFs 	MATLAB Simulation and GUI	Requires MFs tuning for robustness

ACTCS): <i>Automatically adapt AC temperature based on atmospheric temperature conditions</i>	Dew Point Temperature, Occupancy Percentage. Output: AC Temperature Level	<ul style="list-style-type: none"> • 81 rules • COG method 		
Smart Washing Machine: <i>Optimize washing settings for energy and water efficiency</i>	Input: Dirt Level, Load Size, Fabric Type. Output: Wash Time, Water Level, Spin Speed.	<ul style="list-style-type: none"> • Mamdani • Triangular MFs • 27 rules • COG method 	MATLAB Simulation and GUI	Difficulty in accurate sensing and rule expansion
Smart Irrigation System: <i>Control water flow based on environmental conditions</i>	Input: Soil Moisture, Temperature, Light Intensity Output: Watering Duration	<ul style="list-style-type: none"> • Mamdani • Triangular & Trapezoidal MFs • 27 rules • COG method 	MATLAB Simulation and GUI	Requires proper sensor calibration
Smart Traffic Light: <i>Adjust green light duration according to traffic conditions</i>	Input: Number of Vehicles, Queue Length, Number of Lanes Output: Green Light Duration	<ul style="list-style-type: none"> • Mamdani • Triangular & Trapezoidal MFs • 27 rules • COG method 	MATLAB Simulation and GUI	Requires tuning for optimal timing
Fuzzy Logic Application in Smart Air Conditioners Control Systems: <i>Optimize compressor workload using variable speed control</i>	Input: Inside Temperature, Relative Humidity, Room Size Output: Compressor Speed	<ul style="list-style-type: none"> • Mamdani • Triangular & Trapezoidal MFs • 27 rules • COG method 	MATLAB Simulation and GUI	Requires better input/output tuning
Fuzzy Logic in Traffic Light Control System: <i>Optimize traffic signal timing dynamically</i>	Input: Number of Waiting Cars, Fog Level, Time of Day Output: Green Light Duration	<ul style="list-style-type: none"> • Mamdani • Triangular & Trapezoidal MFs • 27 rules • COG method 	MATLAB Simulation and GUI	Limited input range and timing inefficiency between sets

While all selected projects successfully demonstrated the application of fuzzy logic within their respective domains, a key limitation is the absence of standardized performance measurements for direct comparison. Therefore, this study should be viewed as a comparative framework and design analysis rather than an experimental benchmarking study. Future work may incorporate

standardized datasets and performance metrics to facilitate more rigorous quantitative comparisons across different fuzzy logic-based applications.

Generalized FIS Framework and Methodology

Based on the comparative analysis and having the similar fashion of FLC architecture, a generalized FIS framework is presented in Figure 2. The generalized framework begins with the collection of input parameters from sensors or user-defined variables. Then, converted into linguistic variables using MFs during the fuzzification stage. The fuzzy inference engine applies IF–THEN rules to generate fuzzy outputs. Finally, the defuzzification process converts the fuzzy results into crisp output values for system control and dynamic multiple smart system applications.

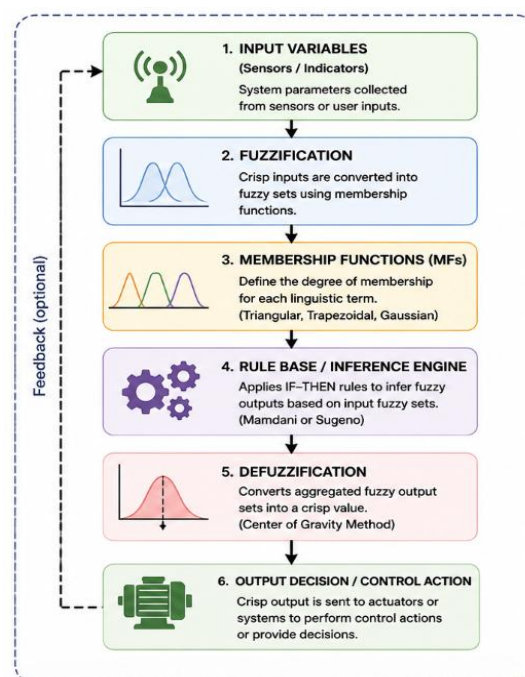


Figure 2: A Generalized FIS Framework

Source: The image was generated with the assistance using ChatGPT based on conceptual designs provided by the authors.

Furthermore, a generalized methodology was also illustrated to represent the development processes as shown in Figure 3. The methodology consists of seven stages, including problem identification, selection of input and output variables, MFs design, rule base development, system implementation, and performance evaluation. The control objectives and requirements were identified, and relevant input, and output variables were selected to represent the system behaviour. The MFs and fuzzy rules were subsequently developed to model human-like reasoning. The systems were implemented using MATLAB simulation and GUI for testing and validation.

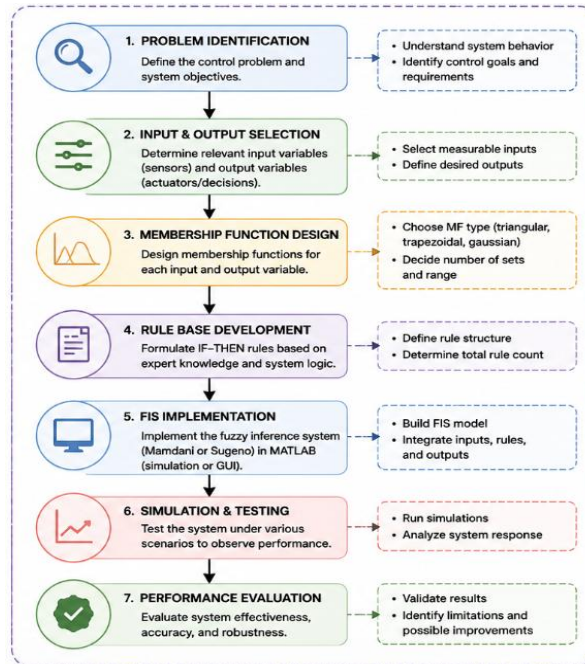


Figure 3: A Generalized FIS Methodology

Source: The image was generated with the assistance using ChatGPT based on conceptual designs provided by the authors.

The generalized framework and methodology demonstrate the flexibility of FIS and provide a reference structural for future endeavours in smart control system development which facilitates the undergraduate's engagement in complex system design and fosters the transition from theoretical learning to practical real-life applications.

Finding and Discussion

The comparative analysis demonstrates that FIS provide a flexible and effective approach for intelligent automation and adaptive control applications. The findings highlight the capability of FLC to model human reasoning, handle uncertainty and generate responsive control decisions. All projects had successfully implemented Mamdani-FIS type with MATLAB software as tools of simulations to handle dynamic conditions. The developed FLC demonstrated practical benefits in improving automation efficiency and adaptive system performance. For example, the fuzzy air conditioning systems adjusted cooling behaviour corresponding to environmental conditions, while the smart irrigation system optimized water usage based on soil and temperature conditions. Similarly, the traffic light systems dynamically modified green light durations according to traffic conditions, indicating the effectiveness of fuzzy logic in real-time control applications.

Nevertheless, the systems still require proper tuning of MFs, rule optimization, and sensor calibration to further improve robustness, accuracy, and overall system performance. Additionally, increasing the number of input variables contributed to rule explosion, which increased system complexity and reduced scalability. Sensor calibration and input parameter selection were also identified as important factors affecting system performance and reliability. Some systems altered heavily on accurate sensor readings and surroundings data, which may affect system reliability in real-world implementations. Overall, the study demonstrates that FIS manage to provide a flexible and practical approach for intelligent control and decision-

making applications. The proposed generalized framework and methodology may serve as impactful references and guideline for future development of fuzzy logic smart control applications especially to undergraduates.

Conclusion

This paper presented a comparative analysis of six fuzzy logic-based smart control systems developed by Mamdani-FIS type. The selected projects covered multiple application domains, including air conditioning systems, washing machines, irrigation systems, and traffic light control systems. The analysis focused on the system objectives, input and output variables, membership function design, rule base construction, defuzzification method, implementation approaches, and system limitations. The findings demonstrated that fuzzy logic provides a flexible and effective approach for intelligent automation and adaptive control in uncertain environments. Despite differences in application domains, all projects shared similar FIS architectures and implementation methodologies, highlighting the adaptability of fuzzy logic in smart control applications. The proposed generalized FIS framework and methodology further provide a significant reference for future system development. Although the systems showed promising performance through MATLAB simulations and GUI implementations, several challenges were identified, including MFs tuning, rule construction complexity, and scalability issues. This study should therefore be viewed as a comparative framework and design analysis rather than an experimental benchmarking study. Future work may focus on real-time implementation, optimization techniques, and integration with IoT or machine learning technologies to further improve system performance and practicality.

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- Acknowledgements:** The authors would like to express their sincere gratitude to the Faculty of Computer Science and Mathematics, Universiti Teknologi MARA, Kedah Branch, for providing the necessary resources and continuous support throughout this research. Special appreciation is also extended to the undergraduate students who contributed to the development of the fuzzy logic-based smart control system projects included in this comparative study, whose efforts significantly enhanced the quality of this paper.
- Funding Statement:** No Funding
- Conflict of Interest Statement:** The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the International Journal of Innovation and Industrial Revolution (IJIREV).
- Ethics Statement:** This study did not involve any human participants, animals, or sensitive data requiring ethical approval. The authors confirm that the research was conducted in accordance with accepted academic integrity and ethical publishing standards.
- Author Contribution Statement:** All authors contributed significantly to the development of this manuscript. Norliana Mohd Najib was responsible for the conceptualization, methodology and analysis, and overall supervision of the study. Noor Azzah Awang handled interpretation of results and discussion. Nur Syafizan Sufter contributed to the literature review, formatting and critical revision of the manuscript. All authors read and approved the final version of the manuscript prior to submission.
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