Performance Comparison of Fuzzy Mamdani and Sugeno in Curtain and Lighting Control

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***Abstract*—Efficient room lighting is essential for user comfort and health. This study implements and compares Fuzzy Mamdani and Sugeno methods in an automatic curtain and lighting control system based on Arduino Uno. The system responds to light intensity changes by adjusting curtains and a dimmable lamp according to LDR sensor values. Tests were conducted under various conditions to evaluate performance. Results show that Sugeno has a faster average response time of 13,898 seconds compared to Mamdani's 15,158 seconds, with a difference of 1,26 seconds. Sugeno also demonstrates better accuracy: for curtain control, it achieved MSE of 347,9368872 and RMSE of 18,65306643, while Mamdani recorded MSE of 570,71862 and RMSE of 23,889718. For dimmer control, Sugeno obtained MSE of 1683,99071 and RMSE of 41,0364559, outperforming Mamdani's MSE of 2679,24 and RMSE of 51,7614. This implementation provides an optimal solution for automatic lighting management to enhance energy efficiency and user comfort.**

Keywords: Arduino Uno, Curtain, Dimmer, Fuzzy Mamdani, Fuzzy Sugeno

I. INTRODUCTION

Technology developments have a significant impact in advancing science and helping human needs. However, advanced technology and automation can also lead to wasteful costs and increased energy consumption. Therefore, energy saving, especially in the use of lighting, is an important issue that needs attention [1], [2], [3]. One of the factors that determine comfort in a work environment is the lighting level. When lighting in the workplace is too bright or too dim and does not meet certain standards, it can worsen visual conditions and reduce work comfort [4], [5]. Light is essential for various human activities such as work, play, study, and exercise. The use of sunlight is an effective way of lighting because its large intensity can illuminate the entire room [6].

Sugeno method was introduced by Takagi, Sugeno, and Kang in 1985. This method is a fuzzy inference method that uses rules in the form of IF-THEN, where the results issued by the system (consequent) are constants or linear equations, not fuzzy sets [7], [8]. The Mamdani Fuzzy Method, introduced by Ebrahim Mamdani in 1975, is part of the Fuzzy Inference System used for inference or best decision making in uncertain situations. This method uses linguistic methods and has a fuzzy algorithm that can be analyzed mathematically, making it easier to understand [9].

Research conducted by Afdal Alhafiz with the title Implementation of Fuzzy Logic Methods on Light Intensity in Arduino-Based Laboratories, which discusses automatic light intensity control systems using the Fuzzy Logic method, shows that the use of fuzzy logic can increase energy efficiency in the room with automatic adjustment of lighting levels based on light intensity [10]. From research conducted by Andi Tenriawaru with the title Multisensor Automatic Light Control System Using Microcontroller-Based Sugeno Inference Fuzzy Logic Control Method, it shows that the application of the Sugeno fuzzy method is effectively able to regulate the status of lights out and on based on input variables obtained from the LDR sensor. Using this approach, the system can respond adaptively to changes in light [7].

Research conducted by Afiat Miftahuddin titled Analysis of Light Intensity Control System in Workspaces Using the Fuzzy Mamdani Method showed that the system is capable of responding to changes in light intensity and that the implementation of the Fuzzy Mamdani method in controlling room lighting can reduce electricity consumption [11].

Previous studies have successfully demonstrated the effectiveness of fuzzy logic methods in lighting automation. However, most research focuses on implementing either Mamdani or Sugeno method individually [7], [10], [11]. While these single-method implementations provide valuable insights into fuzzy-based control systems, there is limited comparative research that evaluates both methods under identical experimental conditions using the same hardware platform and environmental setup.

Based on this research, this research extends the current knowledge by conducting a direct comparative study of Fuzzy Mamdani and Fuzzy Sugeno methods for integrated curtain and lighting control. The comparison aims to provide quantitative performance data (MSE, RMSE, and response time) that can assist practitioners in selecting appropriate methods for similar applications. Additionally, this study implements both methods on resource-constrained Arduino UNO hardware to evaluate their computational efficiency in embedded systems.

Based on previous research, this study develops an Arduino UNO-based automatic curtain and lighting control system using dual LDR sensors. The system implements both Fuzzy Mamdani and Fuzzy Sugeno methods to control stepper motor for curtain positioning and dimmer module for lamp brightness. Performance evaluation uses Mean Squared Error (MSE), Root Mean Squared Error (RMSE), and response time as comparative metrics. This comparative approach aims to provide empirical evidence regarding the practical performance differences between both methods in Arduino-based lighting automation systems.

II. METHOD

The system is designed to regulate lighting and curtain positions automatically based on indoor and outdoor light intensity. Its architecture incorporates four primary components: an Arduino UNO microcontroller, two LDR sensors, a stepper motor for the curtain mechanism, and a dimmer module for the lamp. Two fuzzy-logic approaches—Mamdani and Sugeno—are implemented to determine the optimal curtain and lighting settings.

A. Literature Review

Various previous studies have designed curtain and lighting automation systems based on fuzzy methods, such as Fuzzy Logic, Mamdani, and Sugeno. These studies are an important basis in the development of sensor and Arduino-based systems,

This research builds upon several established concepts from previous studies. The Arduino-based hardware implementation and LDR sensor configuration are adapted from Alhafiz [10], who demonstrated effective light intensity measurement using similar sensor placement. The fuzzy rule structure and multi-input control strategy are informed by Tenriawaru [7], particularly for handling multiple sensor inputs. The Mamdani method implementation, including triangular membership function design, references Miftahuddin [11]. This study extends these foundations by implementing both Mamdani and Sugeno methods for direct comparison, adding automated curtain control, and employing quantitative performance metrics (MSE, RMSE, response time) for systematic evaluation.

This research aims to compare the Fuzzy Mamdani and Sugeno methods in an automatic curtain and light control system based on Arduino UNO and LDR sensors, which is tested directly in a real room. This system is designed to improve the efficiency and convenience of automatic lighting.

B. Fuzzy Logic

Fuzzy Logic is a control method introduced by Prof. Lotfi A. Zadeh in 1965, which deals with uncertain values without requiring complex mathematical equations [12]. Unlike crisp logic, which only recognizes binary values (0 and 1), fuzzy logic introduces degrees of membership between these two extremes [13]. This method maps inputs to outputs using fuzzy set theory to handle uncertainty and complexity [14]. A membership function is a curve that maps input values to membership degrees ranging from 0 to 1. Common types of membership functions include linear (increasing and decreasing), triangular, trapezoidal, and S-curves [15].

C. Fuzzy System

Fuzzy A fuzzy system operates based on rules within fuzzy sets and consists of three main stages. The first is fuzzification, which is the stage of converting definite inputs into fuzzy values using membership functions with degrees between 0 and 1 [16]. Next is the inference stage, which processes fuzzy inputs based on IF–THEN rules to produce fuzzy outputs [17]. The last stage is defuzzification, which converts fuzzy outputs into definite values using methods such as centroid or weighted average [18].

D. Lighting Standards

Adequate lighting is essential for comfort and eye health. According to SNI 03-7062-2004, the ideal light intensity depends on the type of room and the activities performed within it. Residential spaces generally require around 250 lux, while workspaces such as offices and classrooms require between 300–500 lux. Spaces involving detailed activities, such as laboratories, may require up to 2000 lux [19], [20]. Lighting levels are also influenced by factors such as room size, lamp power, and the distance from the light source. These standards help ensure a safe environment and support productivity.

E. System Block Diagram

In Figure 1, this automatic curtain and lighting control system consists of three main parts: input, controller, and output. The input part includes a PIR sensor to detect human presence, two LDR sensors that measure the intensity of outdoor and indoor light, and a button to activate the system. All data from the input sensors is processed by the Arduino microcontroller as the control center. Based on the results of data processing, Arduino will control the motor to move the curtain and adjust the brightness level of the dimmer lamp. The system works automatically where the PIR sensor will turn off the system when there is movement, while the button serves to turn on the system manually.

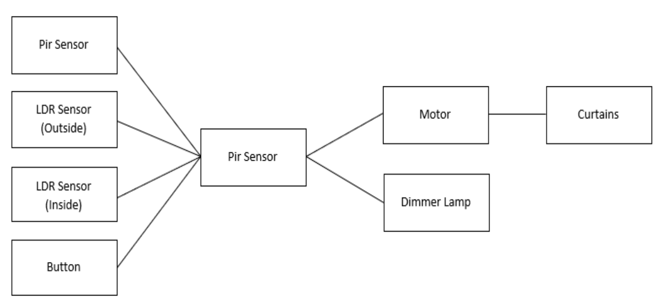

Figure 1. System Block Diagram

F. System Flowchart

As shown in Figure 2, the flowchart illustrates the steps of the Fuzzy Mamdani and Sugeno methods for the Arduino UNO-based automatic curtain and lighting control system. The process begins with the reading of light intensity from both indoor and outdoor LDR sensors. The next step is the initialization of the Fuzzy Mamdani and Sugeno methods, which includes defining fuzzy rules, membership functions, and other relevant parameters. Following this, the Arduino is programmed with control logic based on each respective fuzzy method. The output results from the fuzzy process are then used to determine the curtain's opening level and the lamp's brightness according to the decisions made by the fuzzy system.

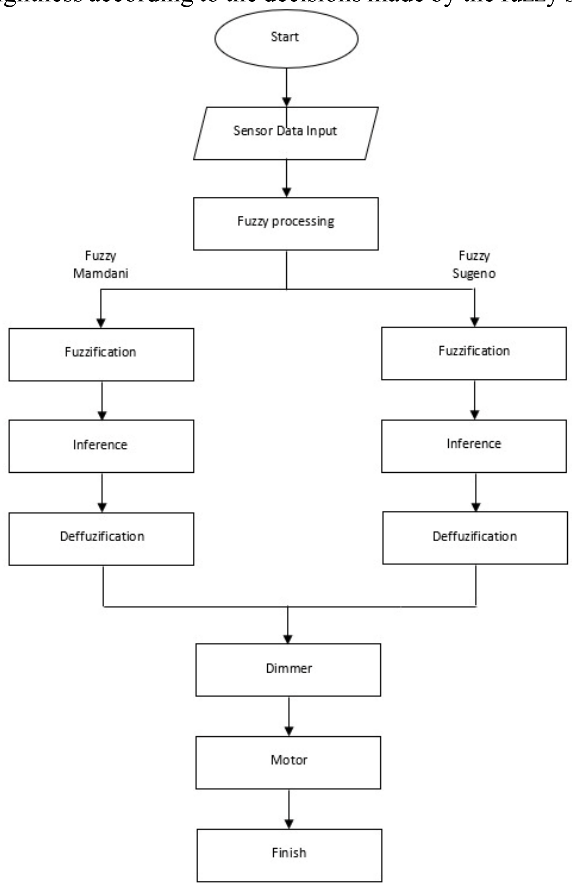

Figure 2. System Flowchart

G. Mechanical Design

As shown in Figure 3, the 3,5 × 3,5 meter room is equipped with a bed, a work desk, a chair, and a window facing south. Two LDR sensors are used: one is placed outside near the window to detect outdoor light intensity, and the other is placed inside the room to monitor indoor lighting levels. An incandescent lamp with a dimmer is installed in the center of the ceiling and is controlled by an Arduino based on data from both sensors.

Figure 3. Mechanical Design

A stepper motor is used to automatically move the curtain in order to regulate natural lighting in the room. This design simulates real-life conditions, allowing the Arduino Uno-based automatic curtain and lighting control system to be tested effectively.

H. Electrical Design

As shown in Figure 4, this Arduino-based automatic system controls an AC lamp and a curtain stepper motor using data from two LDR sensors and a PIR sensor. The LDRs detect indoor and outdoor light intensity, while the PIR sensor detects human presence, which deactivates the automatic system when motion is detected and allows it to be reactivated via a push button. The AC lamp is regulated using a thyristor-based dimmer module according to LDR input, while a NEMA 17 stepper motor with a TB6600 driver operates the curtain using fuzzy logic. A 20x4 LCD displays the system status, and a 12V 5A power supply supports all components, creating an adaptive solution for lighting and curtain control.

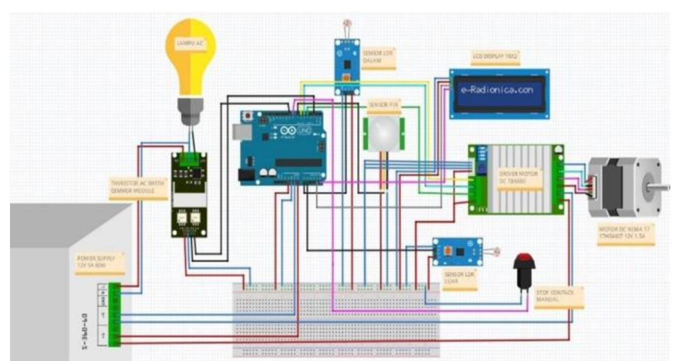

Figure 4. Electrical Design

I. Fuzzy Method Design

This section discusses the design of the methods used in this research, namely the Fuzzy Mamdani and Fuzzy Sugeno methods, which are applied to automatically control curtains and lighting. Table I and Table II present the input value ranges for the indoor and outdoor light sensors, respectively, while Table III shows the corresponding output values.

TABLE I
INDOOR LDR SENSOR RANGE

Conditions	Indoor Sensor Value	Indoor Lux
Light	300 – 550	11.327 – 7,250
Medium	350 – 750	10,518 – 3,948
Dark	550 - 950	7,250 - 646

TABLE II
OUTDOOR LDR SENSOR RANGE

Conditions	Outdoor Sensor Value	Outdoor Lux
Light	30 – 250	15,808 – 12,164
Medium	80 – 750	14,966 – 3,948
Dark	400 – 950	9,710 - 646

TABLE III
OUTPUT VALUES

Curtains (%)	Dimmers (V)
100%	220V
50%	110V
0%	0V

The fuzzy rules define the control strategy based on indoor and outdoor light conditions. The output values represent the nominal target positions: for curtains, 100% indicates fully open, 50% half open, and 0% fully closed; for dimmers, 0V indicates lamp off, 110V represents medium brightness, and 220V represents full brightness. During system operation, the defuzzification process may produce values that vary slightly from these nominal targets depending on the membership degrees of activated rules.

Figures 5 and 6 below show the membership function graphs for the indoor and outdoor light sensors, respectively, each categorized into three criteria: bright, moderate, and dark.

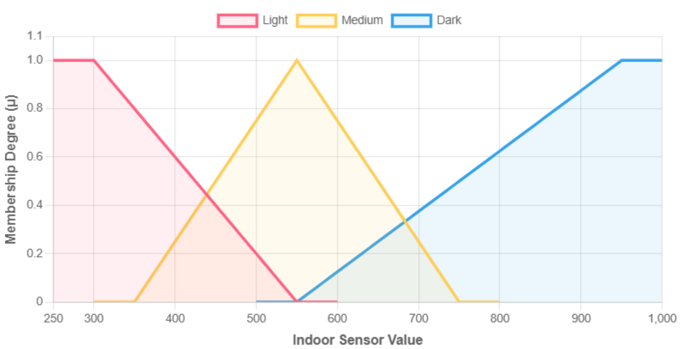

Figure 5. Indoor Sensor Membership Function Graph

$$\mu Light = \begin{cases} 1, & if\ x \le 300 \\ \frac{550-x}{550-300} & if\ 300 < x \le 550 \\ 0, & if\ x > 550 \end{cases}$$

$$\mu Medium = \begin{cases} \frac{x-350}{550-350}, if\ 350 \le x \le 550 \\ \frac{750-x}{750-550}, if\ 550 < x \le 750 \\ 0,\ if\ x < 350\ or\ x > 750 \end{cases} \quad (2)$$

$$\mu Dark = \begin{cases} 0, & if\ x \le 550 \\ \frac{x-550}{950-550} & if\ 550 < x \le 950 \\ 1, & if\ x > 950 \end{cases} \quad (3)$$

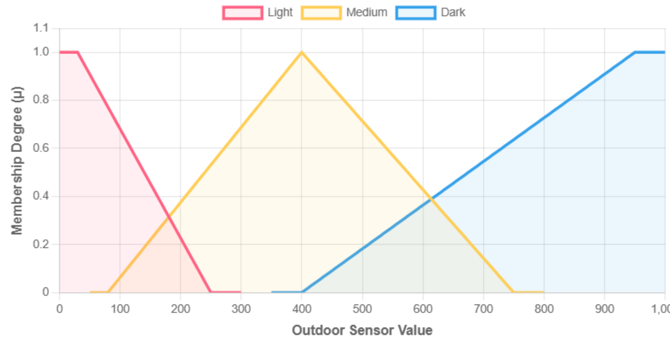

Figure 6. Outdoor Sensor Membership Function Graph

$$\mu Light = \begin{cases} 1, & if\ x \le 30 \\ \frac{250-x}{250-30} & if\ 30 < x \le 250 \\ 0, & if\ x > 250 \end{cases} \quad (4)$$

$$\mu Medium = \begin{cases} \frac{x-80}{400-80}, if\ 80 \le x \le 400 \\ \frac{750-x}{750-400}, if\ 400 < x \le 750 \\ 0,\ if\ x < 80\ or\ x > 750 \end{cases} \quad (5)$$

$$\mu Dark = \begin{cases} 0, & if\ x \le 400 \\ \frac{x-400}{950-400} & if\ 400 < x \le 950 \\ 1, & if\ x > 950 \end{cases} \quad (6)$$

Equations (1) through (6) define the membership functions for indoor and outdoor light sensors. In these equations, x represents the sensor reading value (ranging from 0 to 1023 for Arduino's 10-bit ADC), and μ represents the membership degree (ranging from 0 to 1). The threshold values (e.g., 300, 550, 950 for indoor; 30, 250, 400 for outdoor) were determined through empirical testing to represent typical light conditions in the experimental room. These piecewise linear functions create triangular and trapezoidal membership shapes: decreasing linear functions represent the transition from full membership to zero, increasing linear functions represent the opposite transition, and triangular functions (such as μMedium) have both increasing and decreasing segments meeting at a peak value of 1.

J. Mamdani Fuzzy Method

Fuzzification is the process of converting crisp (numerical) values into degrees of membership based on predefined membership functions. These values indicate the extent to which the data belongs to a particular fuzzy set, such as "Dark", "Medium", or "Light". Commonly used membership function shapes include triangular, trapezoidal, and Gaussian. The result of the fuzzification process is a membership degree (μ), which serves as the basis for the next step in fuzzy inference. This system uses fuzzy rules as shown in Table IV.

TABLE IV
FUZZY MAMDANI RULES

Rules	Indoor	Outdoor	Curtains(%)	Dimmers(V)
1	Light	Light	100	0
2	Light	Medium	50	110
3	Light	Dark	0	220
4	Medium	Light	100	0
5	Medium	Medium	50	110
6	Medium	Dark	0	220
7	Dark	Light	100	0
8	Dark	Medium	50	110
9	Dark	Dark	0	220

Defuzzification is the process of converting the output in the form of a fuzzy set of inference results into a crisp (numeric) value. This process is carried out so that the results of the fuzzy system can be applied in real life, such as to control devices. Common methods of defuzzification include centroid (calculating the weighted average of the area), mean of maximum (taking the average of the values with the maximum membership degree), or bisector (dividing the fuzzy area into two with the same area) [21], [22].

K. Sugeno Fuzzy Method

Fuzzification is the process of converting crisp data from sensors into degrees of membership in fuzzy sets. In the Fuzzy Sugeno method, the inputs from the inner and outer LDR sensors are classified into three linguistic categories: Light, Medium, and Dark, using linear descending, triangular, and linear ascending membership functions. This process allows the system to interpret numerical data in linguistic form for analysis and decision-making purposes. The following are the Fuzzy rules applied in this system in table V.

TABLE V
FUZZY SUGENO RULES

Rules	Indoor	Outdoor	Curtains (%)	Dimmers(V)
1	Light	Light	100	0
2	Light	Medium	50	110
3	Light	Dark	0	220
4	Medium	Light	100	0
5	Medium	Medium	50	110
6	Medium	Dark	0	220
7	Dark	Light	100	0
8	Dark	Medium	50	110
9	Dark	Dark	0	220

Defuzzification is the final stage in the fuzzy logic process, which serves to convert the fuzzy inference results into crisp (numerical) values. In this study, the defuzzification process employs the Weighted Average method [23]. The implementation of defuzzification in the system produces two crisp values, namely the position of the curtain (Z_Curtain) to determine the degree of curtain opening and the dimmer voltage (Z_Dimmer) to regulate the intensity of lamp lighting. These values are calculated by taking the weighted average of the α-predicate (firing strength) of each inference rule and its corresponding singleton output value. The resulting crisp values are then used to control the curtain motor and the lamp dimmer circuit.

L. Comparison of Fuzzy Mamdani and Sugeno

Fuzzy Mamdani and Sugeno have similarities in the fuzzification stage, which converts crisp values into fuzzy using membership functions. The main difference lies in the way of generating the output. The Mamdani method uses linguistic-based rules and produces outputs in fuzzy form. In contrast, the Sugeno method produces output in the form of crisp values directly using linear or constant functions [24], [25].

III. RESULT AND DISCUSSION

This section presents the results of system performance testing, including implementation and comparison of Fuzzy Mamdani and Sugeno methods, curtain and lamp work tests, response time, lux meter analysis of sensor voltage, and manual calculations for fuzzy logic validation.

A. System Testing with the Mamdani Fuzzy Method

In Table VI, the test shows that the Fuzzy Mamdani method is able to adjust the curtain position and lamp voltage based on changes in outside and inside light intensity. For example, when the outside light increases to 258, the curtain opens 50% and the lamp voltage rises to 110V. Under other conditions (inside sensor = 798, outside = 185), the system outputs 55,99% for the curtain and 93,02V for the lamp. These results show an appropriate response to the fuzzy rules and support real-time room lighting efficiency.

TABLE VI
FUZZY MAMDANI TESTING RESULT

Indoor Sensor	Outdoor Sersor	Mamdani Curtains	Mamdani Dimmers
918	157	61,60%	78,02V
890	158	61,36%	78,60V
801	154	62,32%	76,28V
837	186	55,83%	93,49V
815	196	54,30%	97,96V
798	185	55,99%	93,02V
831	243	50,12%	109,73V
816	242	50,15%	109,66V
824	202	53,48%	100,36V
834	224	51,17%	107,00V
825	245	50,07%	109,85V
833	292	50,00%	110,00V
828	241	50,18%	109,58V
825	258	50,00%	110,00V
824	263	50,00%	110,00V
835	279	50,00%	110,00V
828	256	50,00%	110,00V
838	301	50,00%	110,00V
840	329	50,00%	110,00V
849	355	50,00%	110,00V

B. System Testing with the Sugeno Fuzzy Method

In Table VII, the test results show that the Fuzzy Sugeno method is capable of adaptively adjusting the blinds and lamp voltage in response to changes in light intensity. For instance, when the outdoor light intensity increases from 158 to 266, the blinds close by 50% and the lamp voltage increases to 110V. In another condition (indoor sensor = 733, outdoor = 219), the system opens the blinds by 65,16% and reduces the lamp voltage to 76,66V. The system's response, which aligns with the fuzzy rules, demonstrates the effectiveness of the Sugeno method in maintaining comfort while ensuring energy efficiency.

TABLE VII
FUZZY SUGENO TESTING RESULT

Indoor Sensor	Outdoor Sensor	Sugeno Curtains	Sugeno Dimmers
912	158	81,59%	40,51V
932	170	78,19%	47,97V
957	190	72,12%	61,34V
916	266	50,00%	110,00V
851	307	50,00%	110,00V
828	321	50,00%	110,00V
878	288	50,00%	110,00V
849	258	50,00%	110,00V
733	219	65,16%	76,66V
831	215	63,69%	79,88V
733	211	67,33%	71,87V
893	188	72,75%	59,94V
910	206	66,84%	72,95V
876	251	50,00%	110,00V
862	325	50,00%	110,00V
847	273	50,00%	110,00V
859	290	50,00%	110,00V
852	300	50,00%	110,00V
795	254	50,00%	110,00V
856	238	54,97%	99,06V

C. Comparison of Mamdani and Sugeno Performance

In Table VIII, the test results show that the Sugeno method performs better than Mamdani on the curtain and dimmer controls. On curtain control, Sugeno recorded MSE 347,94 and RMSE 18,65, smaller than Mamdani (MSE 570,72 and RMSE 23,89). In dimmer control, Sugeno also excels with MSE 1683,99 and RMSE 41,04 compared to Mamdani (MSE 2679,24 and RMSE 51,76). This advantage is due to Sugeno's simpler and more precise defuzzification process. With smaller errors and better efficiency, Sugeno is more appropriate for fuzzy-based control systems with high accuracy requirements.

TABLE VIII
RESULT OF SYSTEM TESTING

Indoor Sensor	Outdoor Sensor	Actual Curtains	Actual Dimmers	Mamdani Curtains	SE	Mamdani Dimmers	SE	Sugeno Curtains	SE	Sugeno Dimmers	SE
883	356	50	110	50	0	110	0	50	0	110	0
891	398	50	110	50	0	110	0	50	0	110	0
890	413	50	110	50	0	110,1	0	48,7	1,7	113	9
881	467	50	110	49,5	0	111,2	1	43,5	42,3	124,4	207,4
877	460	50	110	49,6	0	111	1	44,1	34,8	123	169
820	485	50	110	49,1	1	112,4	6	40,7	86,5	130,5	420,3
899	302	50	110	50	0	110	0	50	0	110	0
779	283	50	110	50	0	110	0	50	0	110	0
772	272	50	110	50	0	110	0	50	0	110	0
758	280	50	110	50	0	110	0	50	0	110	0
852	236	100	0	50,3	2470	109,3	11946	55,1	2016	98,7	9741,7
735	271	50	110	50	0	110	0	50	0	110	0
695	195	100	0	54,4	2079	97,7	9545	72	784	61,7	3806,9
763	190	100	0	53,9	2125	99	9801	69,3	942,5	67,5	4556,3
747	187	100	0	54,3	2088	98	9604	70,3	882,1	65,2	4251
736	177	100	0	55,5	1980	94,4	8911	73,1	723,6	59,1	3492,8
720	158	100	0	58,2	1747	86,9	7552	76,7	542,9	51,3	2631,7
926	269	50	110	50	0	110	0	50	0	110	0
673	256	50	110	50	0	110	0	50	0	110	0
826	273	50	110	50	0	110	0	50	0	110	0
820	278	50	110	50	0	110	0	50	0	110	0
834	299	50	110	50	0	110	0	50	0	110	0
838	284	50	110	50	0	110	0	50	0	110	0
829	267	50	110	50	0	110	0	50	0	110	0
845	300	50	110	50	0	110	0	50	0	110	0
845	296	50	110	50	0	110	0	50	0	110	0
835	271	50	110	50	0	110	0	50	0	110	0
853	392	50	110	50	0	110	0	50	0	110	0
846	341	50	110	50	0	110	0	50	0	110	0
841	338	50	110	50	0	110	0	50	0	110	0
852	348	50	110	50	0	110	0	50	0	110	0
849	351	50	110	50	0	110	0	50	0	110	0
850	360	50	110	50	0	110	0	50	0	110	0
775	388	50	110	50	0	110	0	50	0	110	0
872	397	50	110	50	0	110	0	50	0	110	0
871	435	0	220	49,8	2480	110,4	12012	46,3	2143,7	118,1	10383,6
861	450	0	220	49,7	2470	110,8	11925	44,8	2007	121,5	9702,3
861	474	0	220	49,4	2440	111,5	11772	42,6	1814,8	126,2	8798,4
843	504	0	220	48,8	2381	113,1	11428	39,4	1552,4	133,3	7516,9
				MSE	570,8	**MSE**	2679,6	**MSE**	347,94	**MSE**	1684,3
				RMSE	23,9	**RMSE**	51,8	**RMSE**	18,65	**RMSE**	41

D. Testing the Condition of Curtains and Lights

In Table IX, the test shows that the system responds well to changes in light intensity. When the outside light is high, the curtain stays at 50% and the dimmer is set around 110V. In contrast, when the outside light is low, the curtains open wider (up to 67,44%) and the lamp voltage decreases (up to 69,06V) to optimize daylighting. These results reflect efficient automatic control in regulating room lighting.

TABLE IX
TESTING THE CONDITION OF CURTAINS AND LIGHTS

Indoor Sensor	Outdoor Sensor	Final Curtains (%)	Final Dimmers (v)
980	388	50	110
883	356	50	110
891	398	50	110
890	413	49,31	111,53
881	467	46,48	117,8
877	460	46,85	116,96
820	485	44,87	121,45
899	302	50	110
779	283	50	110
772	272	50	110
758	280	50	110
852	236	52,72	103,99
735	271	50	110
695	195	63,19	79,66
763	190	61,64	83,24
747	187	62,31	81,63
736	177	64,31	76,79
720	158	67,44	69,06
926	269	50	110

E. Response Time Comparison Testing

In Table X, the test results show that the Fuzzy Sugeno method has a faster response time than Mamdani. The average response time of Sugeno is 13.898 seconds, while Mamdani is 15.158 seconds, with a difference of 1.26 seconds. This difference occurs because defuzzification in Sugeno is simpler, making it more efficient for systems that require a fast response to lighting changes.

TABLE X
RESPONSE TABLE TEST RESULT

Test	Conditions	Mamdani (second)	Sugeno (second)	Difference (second)
1	Normal	15,07	14,29	0,78
2	Outdoor Sensor Closed	10,84	09,63	1,21
3	Indoor Sensor Closed	15,14	14,10	1,04
4	Both Sensors are Closed	10,77	09,34	1,43
5	Outdoor Light Sensor(flashlight)	19,59	18,04	1,55
6	Indoor Light Sensor (flashlight)	15,17	13,86	1,31
7	Second Light Sensor (flashlight)	19,53	18,03	1,5
Average		**15.158**	**13.898**	**1.26**

F. Analysis of Performance Differences

The superior performance of the Sugeno method can be attributed to several factors related to its computational structure. First, the Sugeno defuzzification process uses a weighted average of crisp consequent values, which requires fewer computational steps compared to Mamdani's centroid method that must calculate areas and centroids of fuzzy output sets. This computational efficiency is particularly significant in resource-constrained Arduino UNO hardware (ATmega328P, 16 MHz, 2KB RAM), where every operation affects response time.

Second, the Sugeno method's use of linear or constant consequent functions eliminates the need for complex fuzzy set operations during defuzzification. In contrast, Mamdani performs max-min composition across all activated rules and then computes the centroid of the resulting fuzzy region. This difference becomes more pronounced as the number of active rules increases.

However, the Mamdani method offers advantages in interpretability. Its linguistic output membership functions make the control logic more transparent and easier to tune manually. The trade-off between computational efficiency (favoring Sugeno) and interpretability (favoring Mamdani) should be considered based on application requirements. For real-time embedded systems prioritizing response speed, Sugeno demonstrates clear advantages, while applications requiring human-interpretable control logic may benefit from Mamdani despite slower response times.

G. Comparison of Lux Meter and Voltage Sensor

In Table XI, the test shows a significant linear relationship. In bright conditions (15,910 Lux), the sensor voltage is 0,11 V, while in dark conditions (6 Lux), the voltage is 4,83 V.

TABLE XI
LUX METER AND VOLTAGE SENSOR

Conditions	Lux Meter	Voltage Sensor
Light	15910	0,11 V
Dark	6	4,83 V

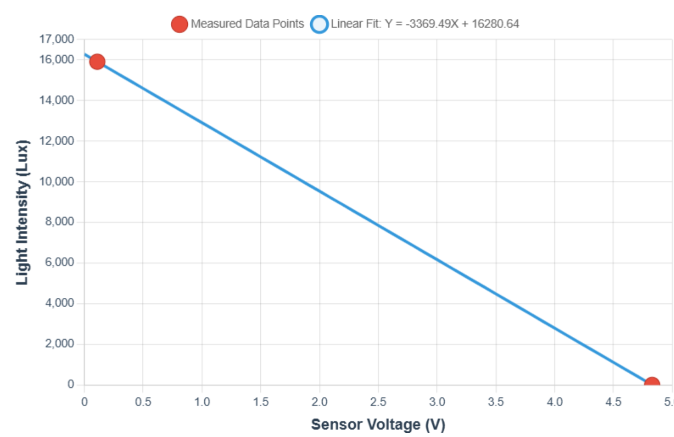

Figure 7. Linear Graphics

In this graph, the relationship between voltage (X) and Lux value (Y) can be formulated as follows:

$$Y = mX + c \quad (7)$$

Where m is the slope of the line (ΔY/ΔX) and c is a constant (the Lux value when the voltage X = 0). The gradient is calculated using the following formula:

$$m = \frac{Lux\ Light - Lux\ Dark}{light\ voltage - Dark\ Voltage} \quad (8)$$

$$m = \frac{15910-6}{0,11-4,83} \quad (9)$$

$$m = \frac{15904}{-4,72} \approx -3369,49 \quad (10)$$

Next, substitute one of the data pairs into the formula
$Y = mX + c$

$$15910 = (-3369,49)(0,11) + c \quad (11)$$

$$15910 = -370,64 + c \quad (12)$$

$$c = 15910 + 370,64 \approx 16280,64 \quad (13)$$

So, the equation for the relationship between voltage and Lux is:

$$Y = -3369,49X + 16280,64 \quad (14)$$

LDR sensor testing shows a linear relationship between sensor voltage and light intensity, with the equation Lux = -3369,49 × Sensor Voltage (V) + 16280,64. In bright conditions (voltage 0.11V), the light intensity reaches 15910 Lux, while in dark conditions (voltage 4.83V), the light intensity drops to 6 Lux. This equation makes it easy to estimate light intensity based on the sensor output voltage.

H. Fuzzy Manual Calculation

Manual fuzzy logic calculations were carried out to verify the consistency between the system's output and the applied fuzzy rules. This process ensures that the implementation of fuzzy logic rules operates accurately and in accordance with the design.

As an example, one sample of the system test results is presented. In this case, the inner sensor value was 891 and the outer sensor value was 398. The output showed that the curtain position using both the Mamdani and Sugeno methods was 50%, while the dimmer values for both methods were also the same, at 110 V. The detailed calculations are presented below.

Inside Sensor: (891)
1) Light = 0
2) Medium = 0
3) Dark = $\frac{891-550}{950-550} = \frac{341}{400} = 0,852$

Outside Sensor: (398)
1) Light = 0
2) Medium = $\frac{398-80}{400-80} = \frac{318}{320} = 0,993$
3) Dark = 0

And here is the Inference (Calculating the Rules Value)

TABLE XII
RULES

Rule	Indoor Sensor	Outdoor Sensor	Min
1	Light	Light	(0,0) = 0
2	Light	Medium	(0,0.993) = 0
3	Light	Dark	(0,0) = 0
4	Medium	Light	(0,0) = 0
5	Medium	Medium	(0,0.993) = 0
6	Medium	Dark	(0,0) = 0
7	Dark	Light	(0.852,0) = 0
8	Dark	Medium	(0.852, 0.993) = 0,852
9	Dark	Dark	(0852,0) = 0

1) Manual Calculation of Fuzzy Mamdani

Curtain Membership set
1) Closed: [0, 25]: Activation = 0
2) Half: [0, 50, 100]: Activation = 0.852
3) Full: [75, 100]: Activation = 0

Calculating Area and Half Moment (Activation = 0,852)

Left Triangle:
1) Left Area = $\frac{1}{2} . 50 \cdot 0.852 = 21,3$
2) Left Centroid = $\frac{(0+50)}{3} = 16,67$
3) Left Moment = $21,3 \times 16,67 = 355,81$

Right Triangle:
1) Right Area = $\frac{1}{2} . 50 \cdot 0.852 = 21,3$
2) Right Centroid = $\frac{(50+100)}{3} = 83,33$
3) Right Moment = $21,3 \cdot 83,33 = 1774,81$
4) Total Area = $21,3 + 21,3 = 42,6$
5) Total Momen = $355,81 + 1774,81 = 2130,62$

Curtain Defuzzification

$$ZTirai = \frac{\text{Total Momen}}{\text{Total Area}} = \frac{2130,62}{42,6} 50,0 \quad (15)$$

Dimmer Defuzzification

Dimmer output membership functions:
1) Off: [0, 110]: Activation = 0
2) Dim: [0, 110, 220]: Activation = 0,852
3) Bright: [110, 220]: Activation = 0

Calculating Area and Half Moment (Activation = 0,852)

Left Triangle [0,110]:
1) Left Area = $\frac{1}{2} . 110 \cdot 0,852 = 46,86$
2) Left Centroid = $\frac{(0+110)}{3} = 36,67$
3) Left Moment = $46,86 \,.\, 36,67 = 1717,84$

Right Triangle (110,220):
1) Right Area = $\frac{1}{2} . 110 \cdot 0,852 = 46,86$
2) Right Centroid = $\frac{(110+220)}{3} = 183,33$
3) Right Moment = $46,86 \,.\, 183,33 = 8594,58$
4) Total Area = $46,86 \,.\, 46,86 = 93,72$
5) Total Moment = $1717,84 \,.\, 8594,58 = 10312,42$

Dimmer Defuzzification

$$ZDimmer = \frac{\text{Total Momen}}{\text{Total Area}} = \frac{10312,42}{93,72} 110,0 \quad (16)$$

2) Manual Calculation of Fuzzy Sugeno

Defuzzification;
with the formula

$$Z = \frac{\sum(\mu i \cdot zi)}{\sum \mu i} = 50 \quad (17)$$

Known:
µi (degree of membership) = 0,852
z1 = 50 (for curtains) and 110 (for dimmers)

The calculation results are:

1) Curtains

$$\frac{0{,}852 \times 50}{0{,}852} = 50 \quad (18)$$

2) Dimmers

$$\frac{0{,}852 \times 110}{0{,}852} = 110 \quad (19)$$

The A manual fuzzy logic calculation was performed to verify the consistency between the system's output and the designed rules. In this case, the indoor sensor reading of 891 is categorized as Dark with a membership degree of 0,852, while the outdoor sensor reading of 398 is categorized as Medium with a membership degree of 0,993. The combination of indoor light is dark and outdoor light is medium activates the fuzzy rule that produces the output curtain is half open and lamp is dim.

In the Fuzzy Mamdani method, curtain defuzzification was carried out by calculating the area and moment of the "Half" membership function (activation 0,852), resulting in a total area of 42,6, a moment of 2130,62, and a final value of 50%. A similar process was applied to the "Dim" membership function for the dimmer, yielding a total area of 93,72, a moment of 10312,42, and a final value of 110 V.

The Fuzzy Sugeno method applied a weighted average approach, where $\mu = 0{,}852$ produced identical results Curtain is 50% and Dimmer is 110 V.

Both methods produced identical outputs, confirming that the implemented fuzzy logic operated as designed and is capable of controlling room lighting automatically, efficiently, and adaptively in response to varying light conditions. Objectives.

IV. CONCLUSION

This research compares the performance of Fuzzy Mamdani and Sugeno methods on the automatic control system of curtains and lights based on light intensity. The results show that the Sugeno method has an average response time of 13,898 seconds, faster than Mamdani which reaches 15,158 seconds, with an average difference of 1,26 seconds. The smallest difference occurs under normal conditions (0,78 seconds), and the largest when both sensors are bright (Sugeno: 18,03 seconds, Mamdani: 19,53 seconds). This advantage comes from Sugeno's simpler defuzzification process using a weighted average. In terms of accuracy, Sugeno is also superior. For curtain control, Mamdani produces an MSE of 570,71862 and RMSE of 23,889718, while Sugeno records an MSE of 347,9368872 and RMSE of 18,65306643. On dimmer control, Mamdani has an MSE of 2679,24 and an RMSE of 51,7614, while Sugeno records an MSE of 1683,99071 and an RMSE of 41,0364559. With an average response time of 8,32% faster and better accuracy, Sugeno's method is considered more suitable for automatic blinds and lighting control systems that require fast response and high precision.

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