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Automation to improve pig welfare using fuzzy logic

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ABSTRACT: One of the challenges in precision livestock farming is controlling the variables that affect production and automation for actuator triggering. Automated systems with fuzzy logic allow the integration of expert knowledge from various contexts, facilitating the adoption of animal welfare practices. The objective of this study was to compare a fuzzy logic-based system model with a proportional control-based system model for regulating environmental conditions in pig pens. Through input variables such as temperature, relative air humidity and ammonia levels, the system output was the activation of fans/extractors and the opening/closing of curtains. MATLAB® software was used to model the systems and simulate actions to promote animal welfare. When comparing the efficiency of the fuzzy logic-based system with the proportional control system, it was observed that the output result of the fuzzy model was faster in 90.1% of the samples, with its average output in rpm being 12.7% higher than the proportional control system. The proposed fuzzy logic control system demonstrates efficiency for use in precision livestock farming processes.

Key words: control systems; rural buildings; precision livestock farming; ventilation

Automação para melhoria de bem-estar em suínos com aplicação da lógica fuzzy

RESUMO: Um dos desafios da pecuária de precisão é o controle das variáveis que afetam a produção e a automação para acionamento de atuadores. Sistemas automatizados com lógica fuzzy permite incorporar o conhecimento de especialistas em diferentes realidades, favorecendo a adoção do bem-estar desses animais. O objetivo deste estudo foi comparar um modelo de sistema baseado em lógica fuzzy com um modelo de sistema baseado em controle proporcional para regulação de condições ambientais em baias em suínos. Por meio das variáveis de entrada como temperatura, umidade relativa do ar e nível de amônia, a saída do sistema era o acionamento de ventiladores/exaustores e a abertura/fechamento de cortinas. Foi utilizado o software MATLAB® para modelar os sistemas e simular ações para promover o bem-estar animal. Ao comparar a eficiência do sistema baseado na lógica fuzzy com o sistema de controle em ação proporcional, observou-se que o resultado de saída do modelo fuzzy foi mais rápido em 90,1% das amostras, sendo em média sua saída em rpm 12,7% maior do que o sistema em ação proporcional. O sistema de controle proposto em lógica fuzzy se apresenta eficiente para uso nos processos de pecuária de precisão.

Palavras-chave: sistemas de controle; construções rurais; pecuária de precisão; ventilação

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Introduction

Modern pig farming requires multidisciplinary efforts to achieve good zootechnical and economic indices, based on investments in facilities, guaranteeing health, reducing environmental impact, food safety and animal welfare. Information technology, combined with precision livestock farming, makes it possible to develop expert systems for decision-making (Pandorfi et al., 2012).

It is crucial to pay particular attention to the thermal environment of the facilities where the animals are kept, as the microclimate and physical characteristics of this environment have a significant impact on the processes of energy transfer, thermal regulation and balance between the animal and its surroundings. According to Emam et al. (2023), microclimatic conditions have a direct influence on the performance of farm animals. The thermal and relative air humidity conditions to which animals are subjected, characterized by thermal comfort indices, have been widely studied (Pereira et al., 2018). In addition, thermal conditions influence a variety of dynamic behaviors and are also an indicator of animal welfare (Santos et al., 2016).

Pigs are homeothermic animals and can perform better if they are in their thermal comfort zone (Fonseca et al., 2019). The thermal comfort zone comprises the ambient temperature range where the animal is able to perform an efficient thermal exchange, which minimizes thermal stress and provides a condition of animal welfare. Since heat stress is one of the main factors limiting productivity in tropical regions, it is difficult to adopt measures to ensure animal welfare (Nunes et al., 2014; Lima et al., 2022).

Animal welfare (AW) studies began in the 1970s, when there was a growing public interest in how animals were raised and treated (Fraser, 1999). In the further development of animal welfare concepts, a lot of research has been done analyzing the animals ability to adjust to the environment, including the various types of production facilities (Galvão et al., 2019). Research in the sector aims to quantify the quality of life of animals (Miele et al., 2011) and enable a better production environment to optimize animal welfare, establishing the concept of precision livestock farming and resulting in a competitive advantage in production with greater added value (Aquilani et al., 2022).

In order to control the amount of heat inside pig facilities, opening or closing the sides of the facilities allows greater control of the microclimatic conditions that can affect the interior. A control system based on fuzzy logic allows parameters for the action of opening curtains at different times, or forced ventilation of exhaust gases, to provide animal welfare and make it possible to use controllers to obtain an automated precision livestock tool.

Fuzzy logic, also known as diffuse logic, arises by assigning degrees of truth to propositions, where the minimum value assigned represents a situation of "totally false", the maximum value assigned represents for the same analysis "totally true" and the other numbers refer to partial truth, that is, intermediate degrees of pertinence in a set, leading to its application in a wide area where Boolean logic, for example, would not apply (Chen & Liu, 2019).

The application of fuzzy logic allows the modeling of controllers that result in the treatment of some variables pertinent to animal welfare (Damasceno et al., 2019). The formulation of fuzzy reasoning consists of three stages: fuzzification, inference and defuzzification. These three stages are widely used in control systems to solve different types of problems in various fields of study (Silva et al., 2019), as fuzzy logic simplifies the assimilation of phenomena through refined adjustments (Amorim et al., 2022).

In contrast to fuzzy logic control, the market offers various types of controllers such as PID (proportional, integral and derivative) controllers. These control actions can act only on the proportional action, or combined, where each action has its own parameter settings and characteristics acting on the controlled system in order to eliminate the error or deviation quickly, stably and accurately (Fuentes et al., 2013; Dias et al., 2020; Fernandes & Santos Neto, 2021).

The proportional controller adjusts the output in proportion to the error between the controlled variable and the desired value for the process. In addition, it allows the control parameters to be modified by establishing a linear relationship between the input and output, which gives great flexibility for various applications. However, proportional action can result in oscillations in the process output, depending on the gain or proportionality constant (Kp), which represents the relationship between the output and input of the controlled process. A high gain reduces the error, which can lead to a tendency to destabilize the system and increase the time needed to control the parameters. On the other hand, a lower Kp results in the opposite effect (Fuentes et al., 2013; Mattiello et al., 2015; Dias et al., 2020; Fernandes & Santos Neto, 2021).

Therefore, the objective of this study was to compare a system model based on fuzzy logic with a system model based on proportional control to regulate environmental conditions in pig stalls.

Materials and Methods

The data used was from an experiment conducted on a commercial pig farm located in the municipality of Elias Fausto - SP, Brazil, situated at 23°08' S and 47°23' O, at an average altitude of 517 m. Environmental parameters were measured over ten days in May 2019, including temperature, relative air humidity and ammonia levels.

Climate data was collected every 15 minutes using a data logger (Onset Hobo® U12-02), with a total of 9 sensors located inside the shed and 2 outside, at a height of 1.5 m above the ground. The parameter values were grouped every hour to be applied to the equations of the fuzzy and proportional systems, generating the output signal in rpm.

The modeling was implemented in Matlab® 6.5.01809 13ª using the Fuzzy Logic Toolbox and Simulink (a tool used for modeling, simulating and analyzing dynamic systems) for the fuzzy logic-based system and the proportional control system, respectively. The project was developed with a controller with three input variables (temperature, relative air humidity and ammonia level) and an activation output, switched by period (similar to a PWM output), setting the on/off time to activate an auxiliary ventilation system and an opening system for air flow circulation (Figure 1).

The physical parameters of temperature, relative air humidity and ammonia were divided into three process measurement conditions, in which the situations were considered optimal (physical parameters do not cause discomfort), intermediate (there is discomfort felt by the animal) and critical (the environment is unsuitable for the process), and their values are shown in Table 1.

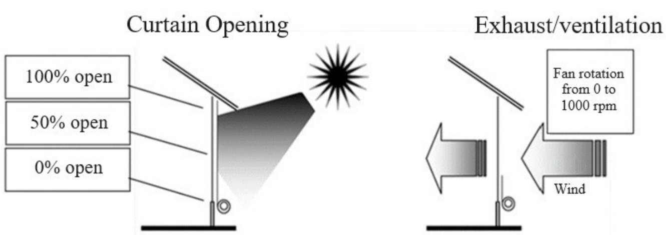
The forced ventilation system (exhaust/ventilation) was activated by changing the engine speed from 0 to 1,000 rpm and the curtains were opened by changing their position from 0 to 100%, divided into five degrees of intensity (optimal comfort, small discomfort, discomfort, severe discomfort and critical), as shown in Table 2.

The fuzzy logic simulation made it possible, after defuzzification, to come up with values for the control variables (rotation and % of curtain opening), in line with precision livestock farming practices. Figure 2 shows the input process (fuzzifier), a set of linguistic rules, a fuzzy inference method and an output processor (defuzzifier) for generating fan drives and curtains at the output.

Table 3 shows the relevance of the welfare variables for temperature, relative air humidity and ammonia concentration. The welfare parameter for temperature, relative air humidity and ammonia concentration in its input process is shown in Figure 3.

The actions of changing the rotation of the fans/exhaust fans and the correct positioning for opening curtains in their output process were classified according to Table 4, and the actions in their output processes are shown in Figure 4.

The parameters were classified by means of bibliographic surveys involving temperature, relative air humidity and ammonia concentration and their influence on pig welfare, as well as expert knowledge. It should be noted that all the



Adapted from Abreu & Abreu (2001).

Figure 1. Structured control actions in a rural installation.

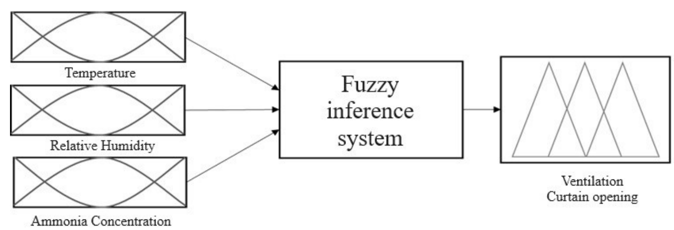


Figure 2. System based on fuzzy rules for activating fans and curtains.

Table 1. Values of the physical parameters of temperature, relative air humidity and ammonia for welfare conditions in pigs.

	Optimal	Intermediate	Critical
Temperature	< 20 °C	> 20 °C < 24 °C	> 24 °C
Relative air humidity	< 55%	> 55% < 70%	> 70%
NH_3 concentration	< 1.0 ppm	> 1.0 ppm < 1.2 ppm	> 1.2 ppm

Table 2. Criteria for activating ventilation based on welfare conditions and degree of comfort intensity for pigs.

Activation criteria	Rotation (rpm)	Curtain opening (%)	Degree of intensity
Three physical parameters in the optimum state	0	0	Optimal comfort
Two physical parameters in the optimal state and one in the intermediate state	250	25	Small discomfort
Two physical parameters in the intermediate state and one in the optimum state	500	50	Discomfort
Three physical parameters in the intermediate state	500	50	Discomfort
Two physical parameters in the intermediate state and one in the critical state	750	75	Severe discomfort
One physical parameter in the optimal state, one in the intermediate state and one in the critical state	750	75	Severe discomfort
Two physical parameters in the critical state and one in the intermediate or optimal state	1,000	100	Critical

Table 3. Definition of the pertinence function for the temperature, relative air humidity and ammonia concentration variables.

Fuzzy set	Type	Range		
		Temperature (°C)	Relative air humidity (%)	Ammonia concentration (ppm)
Optimum	Triangular	[15, 15, 20]	[50, 50, 65]	[0.5, 0.5, 1.0]
Intermediate	Triangular	[15, 20, 25]	[50, 65, 80]	[0.5, 1.0, 1.5]
Critical	Triangular	[20, 25, 25]	[65, 80, 80]	[1.0, 1.5, 1.5]

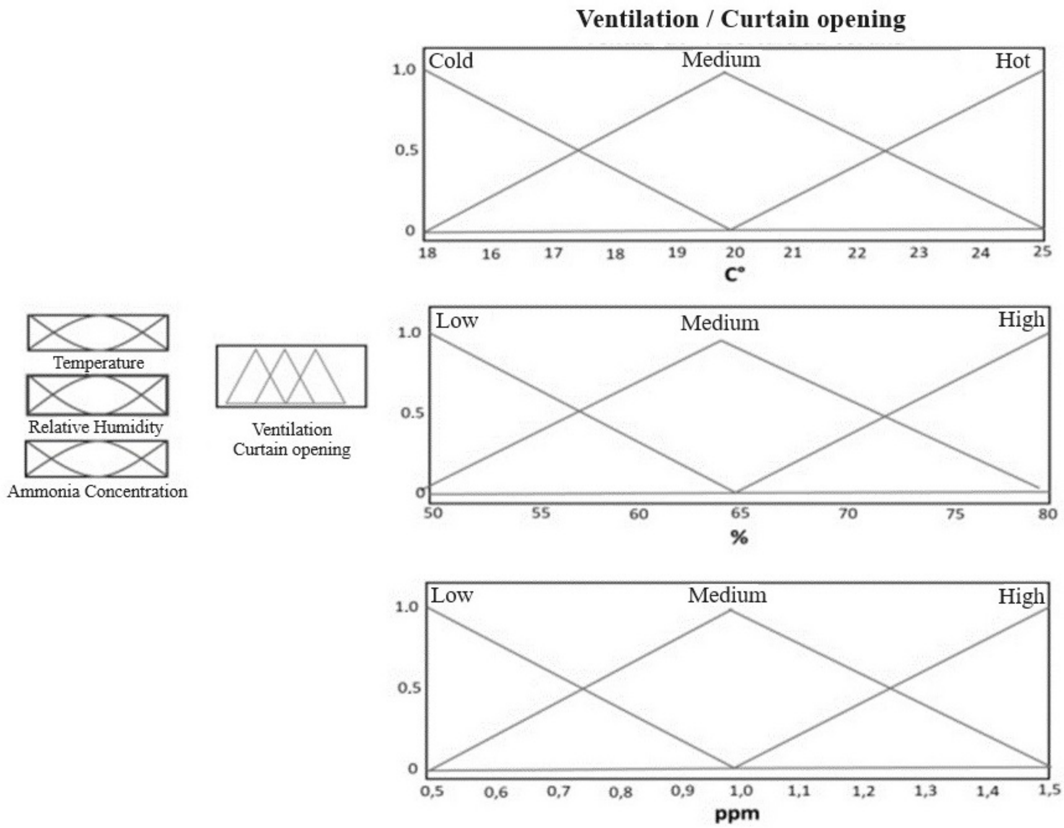


Figure 3. Pertinence functions for the variables temperature, relative air humidity and ammonia concentration in its output process.

Table 4. Definition of the degree of pertinence for the output variable.

Fuzzy set	Type	Range
Optimal	Triangular	[0.0, 0.0, 100]
Small discomfort	Triangular	[0.0, 100, 500]
Discomfort	Triangular	[100, 500, 900]
Severe discomfort	Triangular	[500, 900, 1,000]
Critical	Triangular	[900, 1,000, 1,000]

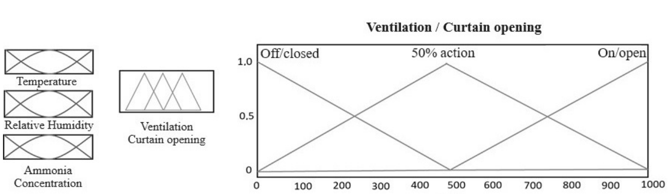


Figure 4. Relevance functions for the actions of changing the rotation and positioning of curtains in the output process.

rules have the same importance, so a weighting factor of 1 was adopted (Amorim et al., 2022).

To check the efficiency of the system modeled in fuzzy logic, a proportional action system was used, which produced a control signal at its output (manipulated variable - MV) proportional to the error, which is the difference between the desired value and the measured value in the process.

In this way, the action of the proportional controller on the system is more intense as the error presented increases. This proportionality is represented by Kp, which defines the controllers amplification factor (gain) set at 50%, this parameter being suitable for linear operation of the control system. The parameters for sensitizing the proportional action were the same as those used in the fuzzy logic modeling, with the desired values (SP) defined in the 'optimum' column of Table 1. In addition, the data in Table 2 was used to define the control action range.

Equation 1 defines the proportional control and Equation 2 the manipulated variable generated in the simulation.

$$PC = Kp \times e(t) \quad (1)$$

$$MV = Kp \times e(t) + IOS \quad (2)$$

where: PC - proportional control; Kp - gain; e(t) - error (difference between the desired value and the value measured in the process); MV - output signal from the controller to eliminate the error; IOS - initial output signal.

The statistical analysis used was descriptive, in which the output speed values were compared and their percentage difference calculated by analyzing the outputs in rpm to determine which control system showed the greatest response for correcting the variables analyzed. In addition, the standard deviation of this speed in each system, the percentage difference between them, and the percentage efficiency when considering the fast and slow response frequencies of each system were calculated.

Results and Discussion

The system based on fuzzy rules was established to find the correct fan/exhaust fan rotations and the correct positioning for opening curtains, providing the animals with a welfare condition in relation to the physical parameters of temperature, relative air humidity and ammonia concentration. Jaroenkhasemmeesuk et al. (2019), when examining energy use and cooling system design in a pig house, determined that the operation of exhaust fans could be optimized to reduce energy costs while maintaining suitable conditions for the animals.

The use of fuzzy logic resulted in three-dimensional modeling of the relationships between the input parameters and the modeling output parameters. Figure 5 shows the surface representation of x and y for the input variables (temperature and relative air humidity, respectively), and z for ventilation/curtain opening.

Arulmozhi et al. (2021) illustrate that inside facilities, temperatures between 16-25 °C and relative air humidity between 60-80% are considered the ideal environment for pigs. With this in mind, the closer the temperatures are to 25 °C and the relative air humidity is above 80%, the more ventilation and curtains need to be opened to make the environment suitable for the animals.

Figure 6, for the relationship between relative air humidity and temperature, shows the action of the welfare parameters in a top view of its three-dimensional modeling, where point "A" was considered to be the "optimal" condition, position "B" as "small discomfort", position "C" as "discomfort", position "D" as "severe discomfort" and position "E" as "critical" for animal welfare.

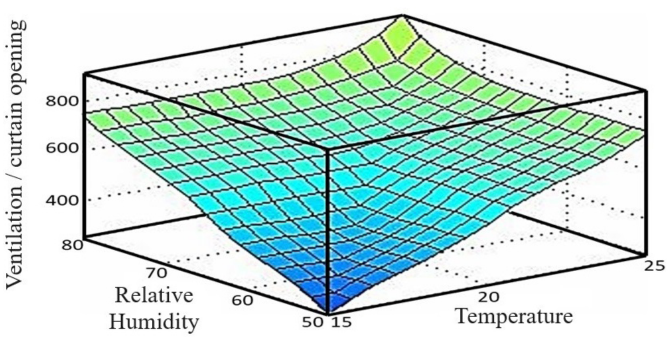


Figure 5. Input versus output parameter surface.

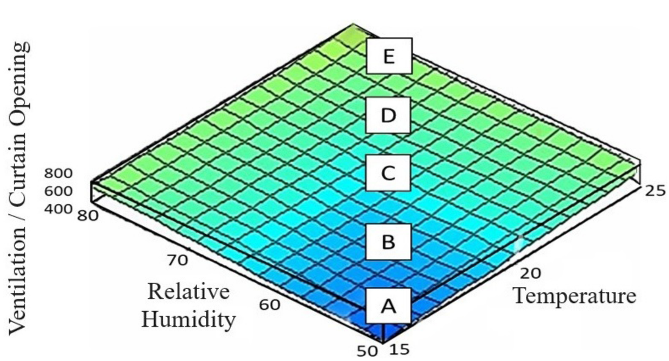


Figure 6. Contour of the relationship between the action of the wellfare parameters of relative air humidity and temperature.

As a result, in the bluest region, the fans are switched off and there is no need to open the curtains, however, in the region considered critical, the fans are started at 1,000 rpm and the curtains are opened 100%. The behavior of the graph is similar when you add the variable ammonia concentration instead of temperature or relative air humidity. In this sense, Chantziaras et al. (2020) argue that the use of mechanical ventilation is essential to reduce respiratory diseases in pig facilities, by allowing them to have better environmental conditions.

Figure 7 shows the rules adopted for the input parameters and output actions in the fuzzy set using the values temperature at 20 °C, relative air humidity at 65% and ammonia at 1 ppm, which took into account the intermediate opening of the curtain and the rotation of the fans.

In Figure 8, by simulating a situation with optimum temperature but critical relative air humidity and ammonia, ventilation at a speed of 682 rpm and curtain opening of 68.2%, it can be seen that the point has a higher degree of pertinence within the discomfort fuzzy set. From this perspective, the use of ammonia concentration for environmental control in pig facilities is crucial. As noted by Rodriguez et al. (2020), this concentration is often not properly considered in the environmental control of these facilities, despite its impact on animal welfare.

Table 5 shows the values obtained for the output speed in rpm for the simulation carried out and the values with proportional simulation using the data processed on the commercial pig farm.

It should be noted that the output of the fuzzy model is higher than that of the proportional model, satisfying the condition of rapid action in the actuators to control the variables studied. In addition, the statistical and efficiency results obtained by comparing the two control models are shown in Tables 6 and 7, respectively.

It can be seen that the efficiency of the fuzzy controller is satisfactory in 90.1% of the samples, with the actuators starting up faster in rpm than the proportional control system. The average speed difference in rpm in the fuzzy control model was 12.7%. According to Tarbosh et al. (2020), the use of fuzzy controllers as speed controllers is attracting strong interest due to their performance.

As indicated by Sreedevi & Paul (2011), the fuzzy controller outperforms conventional controllers in several aspects, including more effective response, reduced settling time and greater ability to cope with variations in system parameters and load. This superiority may justify the increase in standard deviation observed for the fuzzy controller, since its increased sensitivity to changes in parameters results in greater variability in rotation speed.

On the other hand, in seven samples there was a minimum percentage difference between the outputs of the control systems, favoring the proportional system, and

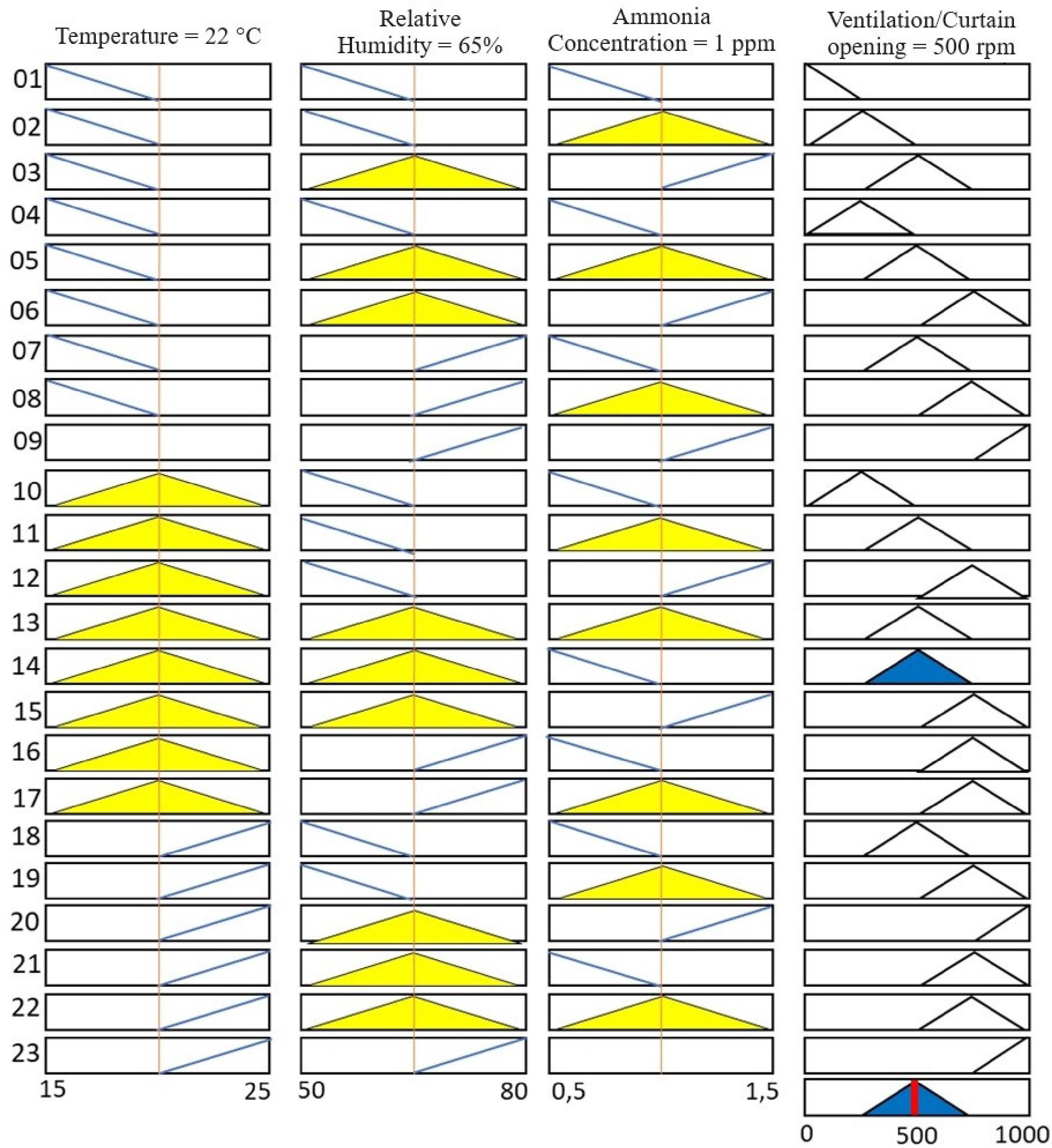


Figure 7. Simulation for temperature at 20 °C, relative air humidity at 65% and ammonia at 1 ppm.

further practical studies may allow us to analyze whether it can be considered within an equality term. In this sense, in a study carried out by Yuan et al. (2021), both conventional controllers and fuzzy logic controllers performed well.

The control model proposed in fuzzy logic, with three variables for swine thermal comfort, proved to be possible to execute as presented by Silva et al. (2019), making it possible to use expert knowledge to train and improve the system. According to Pandorfi et al. (2012), the fuzzy control system provides a foundation for information technologies and precision livestock tools, and is a decision-making system.

Therefore, the proposed fuzzy logic control system is efficient for use in precision livestock processes. According to Nunes et al. (2014) and Lima et al. (2022), pigs perform better if they are in their thermal comfort zone, so it is necessary to adopt actions to ensure animal welfare, and control systems using fuzzy logic meet the characteristics of being efficient in achieving this goal.

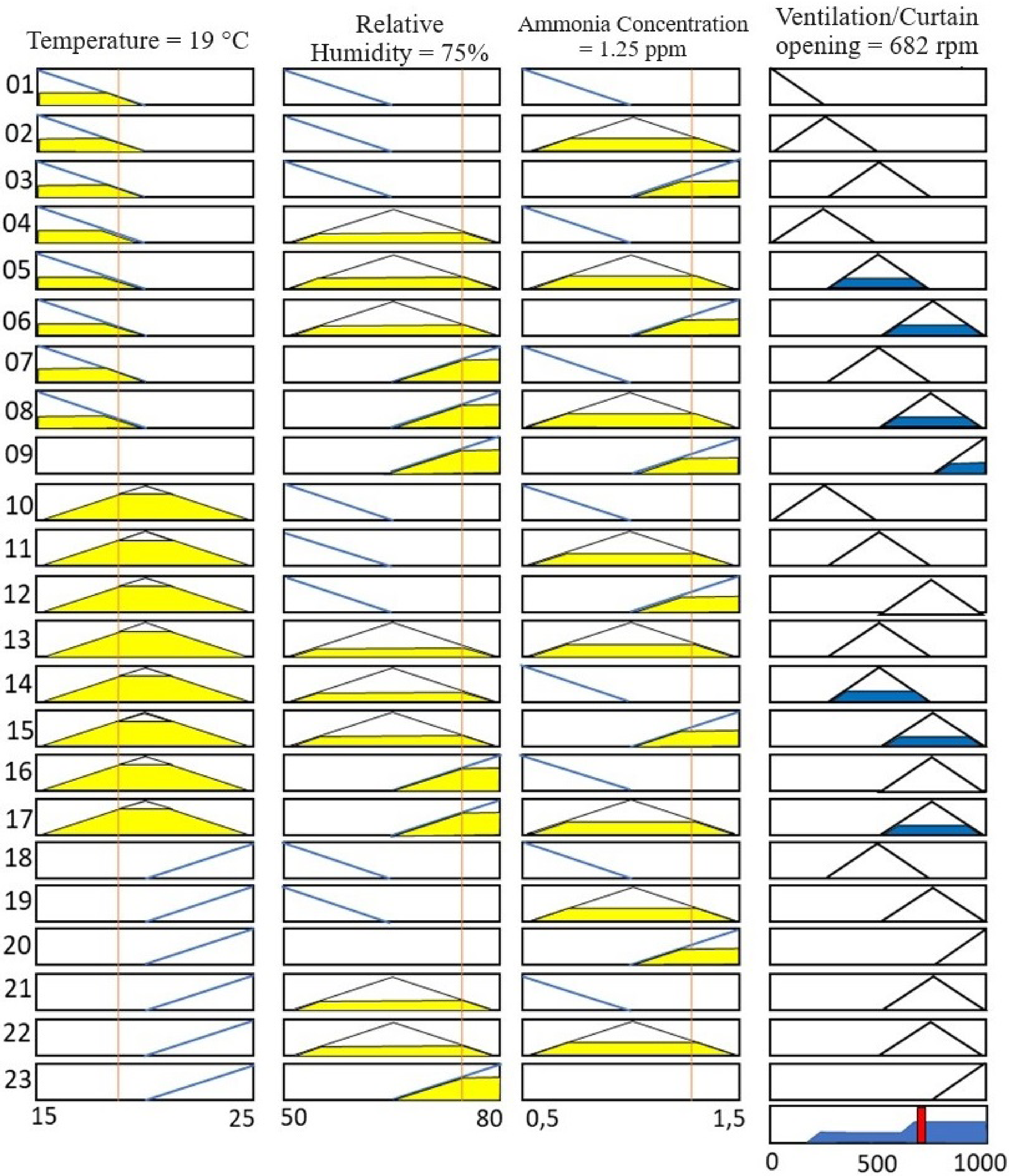


Figure 8. Simulation for temperature at 18 °C, relative air humidity at 75% and ammonia at 1.25 ppm.

Table 5. Output speed for the fuzzy and proportional controller models.

Sample	T (ºC)	HR (%)	NH_3 (ppm)	Ventilation (output)						Speed of control action	
				Fuzzy MatLab (rpm)	Error	Proportional (rpm)	Error	Diff. modulus (%)	Difference (%)	Fuzzy	Proportional
1	25.00	61.00	0.90	593.3	-14.0	590.3	73.4	0.49	0.49	Fast	Slow
2	24.60	72.00	0.80	721.4	114.2	577.1	60.2	20.00	20.00	Fast	Slow
3	24.28	55.00	1.40	617.8	10.6	566.2	49.3	8.34	8.34	Fast	Slow
4	22.67	58.00	0.70	511.7	-95.5	512.5	-4.4	0.15	-0.15	Slow	Fast
5	22.42	74.00	0.90	615.0	7.8	504.4	-12.5	17.99	17.99	Fast	Slow
6	21.99	63.00	1.00	519.5	-87.7	489.9	-27.0	5.69	5.69	Fast	Slow
7	21.03	71.00	1.20	573.4	-33.8	467.0	-49.9	18.56	18.56	Fast	Slow
8	20.13	64.00	1.40	669.0	61.7	428.0	-88.9	36.02	36.02	Fast	Slow
9	23.84	54.00	1.20	611.4	4.2	551.6	34.7	9.78	9.78	Fast	Slow
10	19.90	66.00	1.20	560.1	-47.1	420.2	-96.7	24.98	24.98	Fast	Slow
11	19.90	54.00	1.00	496.6	-110.6	420.2	-96.7	15.38	15.38	Fast	Slow
12	19.90	75.00	0.90	627.9	20.6	507.0	-9.9	19.25	19.25	Fast	Slow
13	19.79	71.00	1.30	614.1	6.9	467.0	-49.9	23.96	23.96	Fast	Slow
14	20.75	70.00	0.60	569.7	-37.5	543.0	26.1	4.69	4.69	Fast	Slow
15	22.18	64.00	0.70	574.7	-32.5	509.7	-7.2	11.31	11.31	Fast	Slow
16	24.06	75.00	1.30	633.0	25.8	558.9	41.9	11.72	11.72	Fast	Slow
17	25.00	52.00	1.50	970.0	362.8	590.3	73.4	39.14	39.14	Fast	Slow
18	27.89	55.00	1.20	500.0	-107.2	686.5	169.6	37.30	-37.30	Slow	Fast
19	28.18	62.00	1.10	500.0	-107.2	696.2	179.3	39.24	-39.24	Slow	Fast
20	21.68	79.00	1.50	885.2	278.0	547.0	30.1	38.21	38.21	Fast	Slow
21	24.97	62.00	1.00	755.2	148.0	589.4	72.5	21.95	21.95	Fast	Slow
22	25.00	79.00	1.40	969.6	362.4	590.3	73.4	39.12	39.12	Fast	Slow
23	24.97	71.00	0.70	793.3	186.0	589.3	72.4	25.71	25.71	Fast	Slow
24	22.92	53.00	1.30	523.4	-83.8	520.9	4.0	0.48	0.48	Fast	Slow
25	22.67	79.00	1.30	738.8	131.5	547.0	30.1	25.96	25.96	Fast	Slow
26	22.26	56.00	1.00	574.2	-33.0	499.0	-17.9	13.09	13.09	Fast	Slow
27	22.05	68.00	1.40	674.9	67.7	492.1	-24.8	27.08	27.08	Fast	Slow
28	21.52	68.00	0.60	612.0	4.8	543.0	26.1	11.27	11.27	Fast	Slow
29	21.50	68.00	1.40	681.3	74.1	473.5	-43.4	30.50	30.50	Fast	Slow
30	21.26	76.00	1.10	660.0	52.8	517.0	0.1	21.67	21.67	Fast	Slow
31	20.97	59.00	1.40	545.3	-61.9	455.9	-61.0	16.40	16.40	Fast	Slow
32	20.80	66.00	0.60	553.3	-53.9	543.0	26.1	1.87	1.87	Fast	Slow
33	20.78	75.00	1.20	635.1	27.9	507.0	-9.9	20.17	20.17	Fast	Slow
34	20.49	69.00	1.40	682.8	75.6	447.0	-69.9	34.54	34.54	Fast	Slow
35	20.45	72.00	1.30	616.6	9.4	477.0	-39.9	22.64	22.64	Fast	Slow
36	20.56	62.00	0.60	470.7	-136.5	543.0	26.1	15.36	-15.36	Slow	Fast
37	20.20	72.00	1.50	798.0	190.8	477.0	-39.9	40.23	40.23	Fast	Slow
38	21.22	65.00	1.20	567.6	-39.6	464.2	-52.7	18.21	18.21	Fast	Slow
39	23.70	53.00	0.70	523.7	-83.5	547.0	30.1	4.45	-4.45	Slow	Fast
40	24.42	69.00	0.80	683.4	76.2	571.0	54.0	16.45	16.45	Fast	Slow
...	...	...	...	...	...	...	...	...	...		
244	24.00	71.00	1.00	603.9	-3.3	557.0	40.1	7.77	7.77	Fast	Slow
245	23.00	76.00	0.60	637.8	30.6	543.0	26.1	14.87	14.87	Fast	Slow
246	22.00	54.00	1.20	510.3	-96.9	490.3	-26.6	3.92	3.92	Fast	Slow
247	20.00	72.00	0.70	577.5	-29.8	509.7	-7.2	11.74	11.74	Fast	Slow
248	24.00	59.00	1.20	592.9	-14.3	557.0	40.1	6.06	6.06	Fast	Slow
249	19.00	55.00	1.30	500.0	-107.2	390.3	-126.6	21.93	21.93	Fast	Slow
250	21.00	58.00	1.50	518.3	-88.9	457.0	-59.9	11.83	11.83	Fast	Slow
251	22.00	61.00	1.30	574.0	-33.2	490.3	-26.6	14.58	14.58	Fast	Slow
252	22.00	73.00	0.70	591.2	-16.0	509.7	-7.2	13.79	13.79	Fast	Slow

Table 6. Average drive speed and standard deviation for fuzzy and proportional controllers.

	Fuzzy system	Proportional system	Difference
Average (rpm)	607.2	516.9	12.7%
Standard deviation (rpm)	110.9	55.37	16.1%

Table 7. Efficiency between the fuzzy and proportional logic control model.

Output speed	Efficiency	
	Fuzzy	Proportional
Fast	90.1%	9.9%
Slow	9.9%	90.1%

Conclusions

The fuzzy logic model for controlling environmental conditions in pig stalls proved to be more efficient than the model for the proportional control system. It is noteworthy that the current test establishes a computational method for interpreting and acting to correct conditions suitable for animal welfare, making it an appropriate control tool for precision livestock studies aimed at controlling environmental conditions within facilities.

It should be noted that the study only took into account air temperature, relative air humidity and ammonia concentration. Studies with more variables that influence the production environment are needed in order to combine them with programmable controllers.

Compliance with Ethical Standards

Author contributions: Conceptualization: AT; Data curation: KOSM; Formal analysis: FLC; Funding acquisition: AT, KOSM; Investigation: AT, CSD, MRMM, TCW, ESH, MNA; Methodology: AT, FLC; Project administration: KOSM; Resources: CSD, MRMM, TCW, ESH, MNA; Software: AT, FLC; Supervision: KOSM; Validation: AT; Visualization: CSD, MRMM, TCW, ESH, MNA; Writing – original draft: AT; Writing – review & editing: CSD, MRMM, TCW, ESH, MNA.

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