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Fuzzy index for swine thermal comfort at nursery stage based on behavior

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Abstract
This work aims to develop and test a computational mathematical model, based on the *fuzzy* set theory, to predict the rate of thermal comfort by means of the swine behavior in relation to their age and to the black globe humidity index for two nursery types. Nursery 1 had brick stalls with fully slatted metal flooring, and nursery 2 had wooden stalls with fully slatted plastic flooring. Nursery style 2 presented a higher frequency of behavior in the condition comfort than nursery style 1, respectively 39,32% and 38,16%. The thermal comfort values for the *fuzzy* system were 3,58% for the standard deviation and 72,86% for the coefficient of determination. The developed *fuzzy* model has proven adequate in predicting thermal comfort by means of the animal's behavior.

Keywords: Thermal environment; fuzzy model; swine confinement facilities; frequency of behavior.

Índice fuzzy para confort térmico de cerdos en la fase de pre-ceba con base en su comportamiento

Resumen
Este trabajo tuvo como objetivo desarrollar y evaluar un modelo matemático computacional, con base en la teoría de los conjuntos fuzzy, para predecir el confort térmico a partir del comportamiento de lechones, en función de su edad y del índice de temperatura de globo y humedad, en dos tipologías de instalación de preceba. La instalación 1 estaba compuesta por corrales de mampostería y piso de malla metálica, y la instalación 2 tenía corrales construidos con tablilla de madera y piso en malla plástica. La instalación 2 presentó una mayor frecuencia comportamental en la condición de confort que la instalación 1, con 39,32% y 38,16% respectivamente. Los valores da tasa de confort térmico estimados por el sistema fuzzy presentaron una desviación estándar media de 3,58% y coeficiente de determinación de 72,86%. El modelo fuzzy desarrollado mostró ser adecuado para la predicción de la tasa de confort térmico a partir del comportamiento de los animales.

Palabras-clave: Ambiente térmico; modelamiento fuzzy; instalaciones para cerdos; frecuencia comportamental.

1. Introduction

The intensive rearing environment influences the comfort and welfare conditions of animals, producing direct effects on its health status and productivity [1]. A way animals demonstrate comfort or discomfort regarding the environment in which they are raised is by their behavior [2], which is a tool utilized to indicate the animal welfare status [3].

The pigs in the nursery stage, particularly in post-weaning early ages have the lower thermal insulation of tissue and fur, suffering from the temperature changes of installation. As a consequence, there is a lower weight gain and feed conversion, affecting the productivity and the permanence time of the animals at this stage [4].

The first reaction of a pig to a temperature variation is a change in its behavior [5]. When in cold thermal conditions, they usually gather up over or near each other. In comfort

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conditions, when lying, they nearly touch one another, while in heat conditions pigs lie around scattered [6,2]. According to [7] and [8], under thermal stress conditions, pigs show a reduced frequency of feeding, standing, walking, and nuzzling behaviors.

Understanding the animal behavior and their small variations due to environmental thermal changes is necessary in order to develop models that simulate welfare from responses of the animal to the environment [9].

In this regard, mathematical techniques and sensors allow the processing of diversified information about the production process, adding precision to animal production-related actions [10]. The fuzzy sets theory is a mathematical technique that has been adopted to predict situations such as the environmental comfort of facilities [11,12], physiological parameters [13-15], and occupation rate [16].

The Fuzzy Set theory was introduced by Lotfi Asker Zadeh in 1965 as a mathematical theory that generalizes the classical theory of sets. A fuzzy set is defined mathematically by assigning a value, which reflects the degree of the pertinence of the individual to the set. This degree of pertinence varies in the range of 0 to 1 and represents the similarity of this individual the characteristics that give identity to the set [17].

The fuzzy mathematics is a highly flexible structure that allows the integration of different types of information to formulate conclusions. The theory addresses uncertainties through the semantic or linguistic reasoning, providing an analysis of rules or assumptions that can be altered or updated according to the knowledge of the subject matter [18].

Given this scenario, the present study aimed to develop and test a computational mathematical model, based on the fuzzy set theory, to predict thermal comfort by analyzing the behavior of piglets according to age and two thermal variables in two nursery types.

2. Material and methods

2.1. Description of facilities

This study was carried out in two swine nursery facilities of Niterói Farm, located in Lavras-MG, Brazil (21º 14' S latitude and 45º 00' W longitude; 918 m altitude), from August 22 to September 25, 2014. According to the Köppen classification, the climate of the region is a subtropical rainy temperate (mesothermal) Cwa type with dry winters and rainy summers, with an average annual temperature of 20.4 ºC [19].

The farm had a full-cycle swine production system, i.e., animals were confined from birth to slaughter.

Nursing facilities were intended for the production of commercial hybrid swine for 35 days. Animals entered the nurseries at 21 days of age and left them at 56 days of age.

The diet was prepared on the farm according to the nutritional requirements and specific intake of the animals in this production stage, provided in a feeder with automatic distribution. Water was supplied by automatic nipple drinkers with no restrictions to consumption.

Nurseries were oriented in the east-west direction and had the same external structure, with 2.40 m-high metal columns, gable roofing with 30% slope, fibrocement tiles with 6 mm thickness supported by a metal structure without a louver and 0.45 m eaves. The sides were fully covered with yellow canvases with adjustable height.

a) b)

Figure 1. Internal structure of Nursery 1 (a) and Nursery 2 (b)
Source: The authors.

Nurseries had different internal structures. Nursery 1 measured 31.02 × 10.38 m (length × width) and had a 0.90 m-long central corridor with 1.94 × 4.00 m-sided stalls. Suspended 0.50 m above the ground, stalls were made of masonry, with 0.68 m in height, equipped with a 0.32 m-high protective metal grid above the masonry wall and around the stall. Flooring was a metal slatted type, with a 1.00 × 1.50 m central concrete part where the automatic feeder was located. The nipple drinker was located on the left side of the stall. The heating system was provided by 250 W infrared bulbs fixed 0.40 m from the concentrate, at a height of 0.55 m. Nursery 1 was closed at every three stalls up to the roof by translucent corrugated sheets (Fig. 1a) and its housing capacity was 720 animals, with 24 piglets per stall (two litters).

Nursery 2 measured 23.61 × 10.10 m (length × width) and had a 0.90 m-long central corridor with twelve 1.94 × 4.00 m-sided stalls. Stalls were closed with wood laths with 0.80 m in height and slatted polyethylene floor at the level of the central corridor. Below the floor level was a 1.50 m deep ditch for waste. The feeder, the drinker, and the heating system were positioned as in nursery 1. At every three stalls, Nursery 2 was closed by concrete slabs at the same height as the stall (Fig. 1b), and its housing capacity was 576 animals, with 24 piglets per stall (two litters).

2.2. Behavior

To evaluate the behavior of the animals, one sample of six piglets from each nursery was observed in the stalls intended for the experiment. Observations were conducted during 10 non-consecutive days, from 07h00 to 17h00, every 10 min.

The quantified behaviors were based on the ethogram proposed by [20] and [2], as follows: lying (L) - when the animal lay alone, gathering (G) - when the animal lay together with the others, wallowing (W), eating (E), sitting (S), standing/walking (SW), and showing agonistic behavior (AB). Data referring to behavioral variables were analyzed non-parametrically.

To evaluate the comfort condition of the animals, the frequencies of the behaviors named nuzzling (N), eating (E), sitting (S), and standing/walking (SW) were added together, as they represent some of the natural behaviors of these animals [21].

2.3. Environmental parameters

In the nurseries, there was a divider at every set of three stalls, forming a microenvironment between them. To better represent it, thermal comfort, air quality, and sound pressure level data were collected from the central stall of the set. Air temperature, air relative humidity, and black globe temperature were collected automatically using dataloggers (Hobo, U12-013) with an accuracy of ± 0.5 °C, at 10-min intervals, for 24 h, for the 35 days during which the piglets remained in the nurseries.

Sensors were coupled to the dataloggers and placed in the globe for its temperature collection. To prevent interferences from the heat emitted by the heating system in the measurements, the datalogger was installed at a height of 0.80 m and 0.70 m apart from the heating system. For the same reason, the black globe was installed at a height of 0.55 m and placed 0.50 m from the heating system. In the nurseries' external environment, the datalogger and the globe were also installed at the same height as those inside the stalls.

The black globe humidity index (BGHI) was calculated based on the thermal environment data using Eq. 1 below, developed by [22]:

$$BGHI = BGt + 0.36\,DPt - 41.5 \quad (1)$$

Where BGt is the black globe temperature (°C) and DPt is the dew point temperature (°C).

2.4. Fuzzy model

Data pertaining to environment and frequency of behavior in thermal comfort condition were used in the development of a fuzzy mathematical model, in which the age of the animals (days) and the black globe humidity index (BGHI) were used as input variables, as they directly influence the animals' behavioral response. Based on the input variables and using the experimental data collected during field analyses as reference, the fuzzy model predicts the output variable Thermal comfort index of the animals based on their behavior.

Based on the data collected from the field experiment for the two nurseries evaluated, 115 datasets (100%) were selected, in which the characteristic thermal comfort behavior had a direct influence of age and thermal environment conditions. Of this total, 43% (50 datasets) were used in the development of the membership and rule functions and 57% (65 datasets) were used to test the developed model.

The analysis was performed using Mamdani's fuzzy inference method, whose response is a fuzzy set originating from the combination of input values and their respective degrees of membership, by the minimum operator, and then by overlapping the rules by the maximum operator [15].

The input variable Age was adjusted as a function of the period of life of the animals during the experiment (26; 56); this interval was divided into five membership functions (Table 1).

Table 1.
Fuzzy sets for the input variables.

Variable	Fuzzy sets
Age	Age 1 [26.0; 33.5] Age 2 [26.0; 41.0] Age 3 [33.5; 48.5] Age 4 [41.0; 56.0] Age 5 [48.5; 56.0]
BGHI	Level 1 [60; 62] Level 2 [60; 66] Level 3 [62; 70] Level 4 [66; 74] Level 5 [70; 78] Level 6 [74; 82] Level 7 [78; 84] Level 8 [82; 84]

Source: The authors.

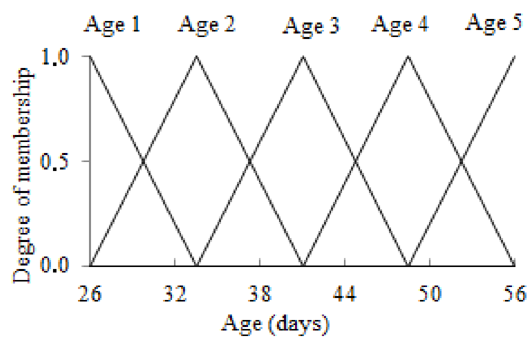

Figure 2. Membership curve for the input variable Age.
Source: The authors.

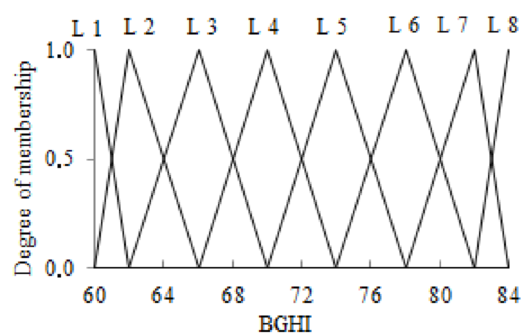

Figure 3. Membership curves for the input variable BGHI.
Source: The authors.

For the BGHI variable, the interval was determined based on the observed thermal data (60; 84), divided into eight levels (L) corresponding to the pertinence functions (Table 1).

The domains in the intervals of the input variables Age and BGHI are presented in Fig. 2 and Fig. 3. The triangular pertinence curve model was adopted, as it fits better the input variables' data.

For the output variable, Thermal comfort index (%), the behavior data were clustered according to characteristic behavioral patterns related to thermal comfort: eat, wallow, sit, and standing/walk. These behavioral traits were quantified in frequencies, and their values determined the intervals for the eight pertinence functions represented by Degree (D) according to Table 2.

Table 2.
Interval of fuzzy sets for the output variable Thermal comfort index (%).

Fuzzy sets	Interval
Degree 1	[0; 14]
Degree 2	[0; 29]
Degree 3	[14; 43]
Degree 4	[29; 57]
Degree 5	[43; 71]
Degree 6	[57; 86]
Degree 7	[71; 100]
Degree 8	[86; 100]

Source: The authors.

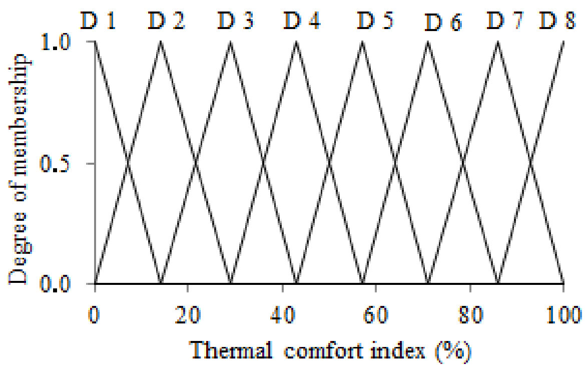

Figure 4. Membership curve for the output variable Thermal comfort index (%).
Source: The authors.

Table 3.
Composition of the rules system as a function of the input variables Age and BGHI

Age \ BGHI	L 1	L 2	L3	L 4	L 5	L 6	L 7	L 8
Age 1	D 4	D 5	D 5	D 3	D 1	D 2	D 4	D 3
Age 2	D 2	D 2	D 4	D 5	D 5	D 2	D 2	D 1
Age 3	D 7	D 7	D 6	D 2	D 3	D 3	D 3	D 2
Age 4	D 1	D 2	D 4	D 2	D 3	D 3	D 3	D 3
Age 5	D 2	D 3	D 4	D 3	D 3	D 4	D 3	D 2

Source: The authors.

After a preliminary adjustment test, the triangular model was used for the pertinence functions of the output variable, according to Fig. 4.

The fuzzy rules system was created based on the set of data obtained experimentally, on information from the literature, and with the aid of experts, in the form of linguistic sentences.

Three experts were selected according to the fuzzy expert selection methodology proposed by [23] and utilized by several authors [24-26]. These experts have experience in ambience and animal behavior, and all have more than 10 years of work in the respective areas, characterizing their mastery of the subject matter. This characteristic is desirable from an expert [27], given their direct influence in the reliability and quality of results [28-29].

According to the combinations of the input data, 40 rules were defined, as described in Table 3. For each rule, the weighting factor of 1 was assigned.

The weighting factor of 1, usually adopted as default, was chosen because it showed to be appropriate for the proposed model based on the response of the results obtained with the simulations. Moreover, this value has been adopted in several fuzzy models reported in the literature [30-33].

Based on the rules system will be performed fuzzy inference (example: *SE* Age is Age 2 *AND* BGHI is L3 *THEN* thermal comfort Index is Degree 4). Immediately after the inference, the defuzzification process is performed where the output linguistic variable is converted into a numerical value [34].

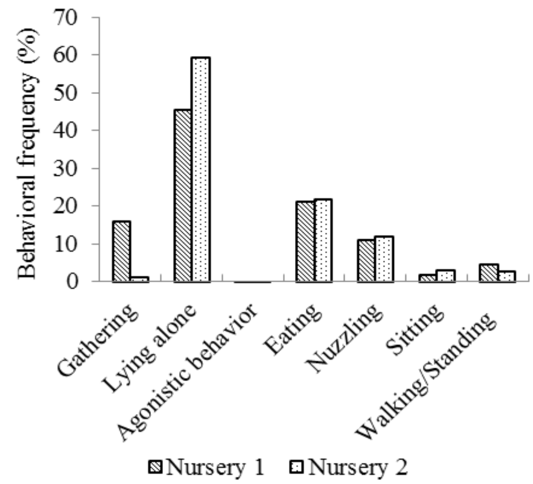

Figure 5. Behavioral frequency (%) of the animals in Nursery 1 and Nursery 2.
Source: The authors.

3. Results and discussion

The behavioral frequencies of the piglets observed in Nurseries 1 and 2 are shown in Fig. 5. The frequencies of the gathering, lying alone, agonistic behavior, eating, nuzzling, sitting and walking/standing behaviors between the two nurseries were close. The gathering behavior was more frequent in Nursery 1, while lying was more common in Nursery 2.

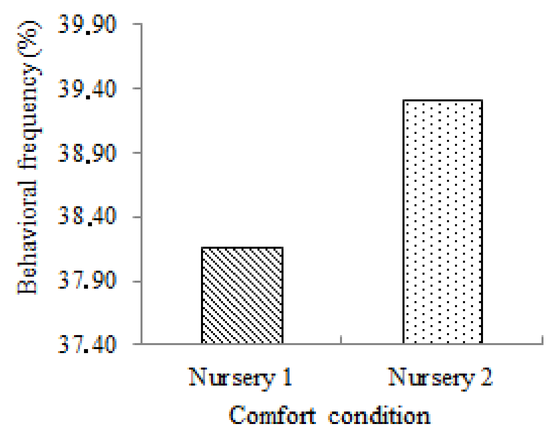

Figure 6. Behavioral frequency (%) in comfort condition in Nursery 1 and Nursery 2.
Source: The authors.

Table 4.
Comparison between thermal comfort indices (%) observed and simulated by the fuzzy model.

Age (days)	BGHI	Thermal comfort index (%)			Age (days)	BGHI	Thermal comfort index (%)		
		Measured	Fuzzy	Std. deviation			Measured	Fuzzy	Std. deviation
26	60	36.11	43.00	30.41	42	76	33.33	28.62	20.23
26	67	52.78	47.74	33.76	47	69	44.44	33.34	23.57
26	71	30.56	24.33	17.21	47	75	27.78	28.65	20.26
26	74	2.78	4.33	3.06	47	78	25.00	28.65	20.26
26	62	55.56	57.00	40.31	47	80	27.78	28.62	20.23
26	75	11.11	9.87	6.98	47	81	27.78	28.65	20.26
26	79	25.00	23.24	16.43	47	82	38.89	28.65	20.26
28	75	22.22	27.76	19.63	49	72	16.67	21.50	15.20
28	78	25.00	14.35	10.15	49	75	38.89	29.99	21.21
28	71	41.67	33.44	23.65	49	81	30.56	29.99	21.21
28	77	25.00	26.90	19.02	49	82	30.56	28.67	20.27
28	81	36.11	33.29	23.54	49	83	36.11	26.95	19.05
33	63	20.00	25.06	17.72	49	73	36.11	24.56	17.37
33	77	38.89	27.49	19.44	49	74	19.44	28.67	20.27
33	78	16.67	14.33	10.14	49	79	19.44	29.99	21.21
33	80	13.89	18.45	13.05	49	78	33.33	29.93	21.16
33	70	58.33	53.63	37.92	54	67	44.44	33.43	23.64
33	81	25.00	17.70	12.52	54	70	22.22	24.34	17.21
35	67	47.22	43.81	30.98	54	73	19.44	24.53	17.35
35	74	47.22	49.04	34.68	54	79	44.44	38.42	27.17
35	71	50.00	43.52	30.77	54	75	33.33	32.68	23.11
35	70	41.67	45.10	31.89	54	66	44.44	43.00	30.41
35	75	36.11	42.05	29.74	54	68	25.00	30.98	21.91
35	72	50.00	41.62	29.43	54	71	36.11	24.34	17.21
40	77	36.11	31.81	22.49	54	74	22.22	28.65	20.26
40	75	33.33	31.81	22.49	54	77	36.11	38.42	27.17
40	74	41.67	34.22	24.20	54	78	38.89	38.42	27.17
40	78	33.33	26.26	18.57	56	72	38.89	28.62	20.23
40	73	33.33	30.04	21.24	56	80	38.89	35.62	25.19
42	72	19.44	21.50	15.20	56	74	30.56	28.67	20.27
42	79	36.11	28.65	20.26	56	81	27.78	32.66	23.09
42	80	36.11	28.62	20.23	56	78	44.44	43.00	30.41
42	73	27.78	24.56	17.37					

Mean = 3.58

Source: The authors.

The comfort condition observed through the eating, nuzzling, sitting, and standing/walking behaviors are illustrated in Fig. 6. Nursery 2 showed a higher percentage of behavioral frequency in the comfort condition than Nursery 1: 39.32% and 38.16%, respectively. These percentage values show that less than 50% of the time during which animals remain in the nursery is comfort conditions.

The thermal comfort index obtained by the fuzzy model, as well as the values observed experimentally and the standard deviation, are displayed in Table 4.

The standard deviation is a measure of the variability or dispersion of the data, and as the deviation increases, so will be the dispersion of the data.

The average standard deviation of the fuzzy model in relation to the values observed experimentally was 3.58%. The highest standard deviation observed was 8.32%, and the lowest was 0.33%.

To measure the quality of the model as regards its ability to correctly estimate the values of the response variable, we calculated the coefficient of determination (R^2, %), as shown in Fig. 7. The R^2 obtained indicated that 72.86% of the variation can be explained by the model.

The fact that the animals from Nurseries 1 and 2 remained most of their time lying without touching each other may be related to the thermal discomfort in the facility, as reported by [6] and [2]. Another aspect to be considered is the frequency of the natural behavior of the animals − eat, wallow, sit and standing/walk −; according to [8], a reduction of these behaviors may be related to discomfort of the animal due to thermal stress.

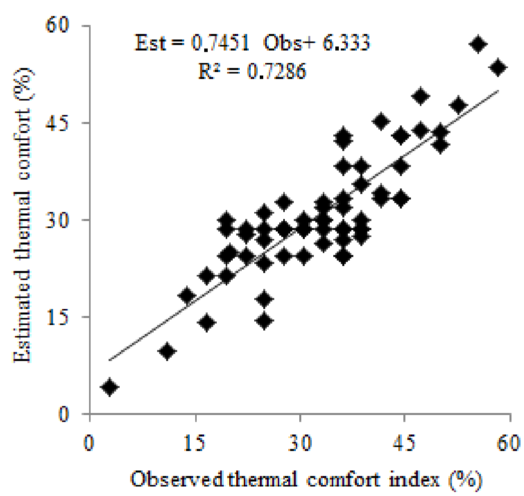

Figure 7. Behavioral frequency (%) for the thermal comfort index.
Source: The authors.

Studies on the occupation rate in dairy cattle facilities conducted by [16] have shown an average standard deviation of 3.93% and a determination coefficient of 75.45%, demonstrating the efficiency of the model developed for the simulated data.

Estimating the weight of Japanese quail eggs, [35] obtained a coefficient of determination of 66.80%. According to these authors, the developed fuzzy model provides a realistic estimate of egg weight.

The fuzzy model for predicting feed intake, weight gain, and feed conversion of broilers developed by [15] found the respective standard deviations: 4.31 g, 4.76 g, and 0.02 g g-1, as well as the following coefficients of determination: 99.8, 99.5, and 97.6%, showing to be adequate for the prediction of the analyzed variables.

The coefficient of determination found in the present study was higher than that found by [35], lower than those obtained by [14], and close to those observed by [16].

Based on the exposed literature and the coefficient of determination found here (72.86%), the developed model satisfactorily estimates the response-variable values and can thus be used to determine thermal comfort in swine nursery facilities.

4. Conclusions

The swine behavior can be used to characterize the thermal comfort condition of facilities.

Based on the behavioral analysis, piglets from both nurseries remained less than 50% of their confinement period under comfort conditions, and Nursery 2 was more comfortable than Nursery 1.

The fuzzy model developed as a function of piglet age and BGHI showed to be suitable for predicting the thermal comfort index based on the animal behavior, displaying low standard deviations and high correlation with the data measured during the field experiment. Therefore, it can be used as an instrument in decision-making regarding alterations in the thermal environment, preventing losses and providing better production rates.

Therefore, new studies aiming at the characterization of the comfort condition, by means of rapid responses of the animal to the thermal stress suffered, being this one, of clear and objective interpretation to the man, is of paramount importance for the animal production that seeks, every day more the adoption of welfare practices.

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