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(Article begins on next page)

Modelling the spatial distribution of THI in a cattle barn from data of a smart monitoring system

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Abstract— The study highlights the importance of monitoring and visualizing the Temperature-Humidity Index (THI) in farm buildings due to its direct impact on livestock health, productivity, and welfare. To address the limitations of traditional monitoring techniques, a Smart Monitoring System (SMS) was employed in a study case to gather real-time THI measurements from various indoor sampling points within an experimental livestock barn. This system integrates temperature and humidity sensors, enabling automatic, remote and continuous data collection. To visualize the THI distribution throughout the farm and overcome data sparsity, the Discrete Sibson Interpolation method was employed. This method effectively interpolates the collected THI data onto a three-dimensional grid, providing a comprehensive representation of the THI distribution. The study involved the definition of spatially continuous distributions that can be visualized through various types of graphs, supporting the identification of meaningful insights about the spatial and temporal trends of indoor THI in livestock buildings. The results obtained from the pilot farm investigation revealed the presence of critical zones with high THI values, which can affect limited areas of the barn volume, even in periods when the average THI of the barn is below the alert threshold. It is important to identify such localized anomalies of THI, because they negatively impact livestock welfare and subsequently reduce the productive levels of the herd. The research addresses the limitations of the analysis of discrete data and average spatial values by employing data processing for interpolation and visualization and the results demonstrates the significance of monitoring THI in livestock barns through SMSs. The findings of this investigation offer valuable insights and practical advice for farmers and stakeholders in developing PLF tools for the analysis and control of the indoor environment of barns, to optimize livestock conditions and mitigate the negative effects of discomfort caused by hot weather conditions.

Keywords— *temperature-humidity index, smart monitoring systems, three-dimensional representation, animal welfare, spatial interpolation*

I. INTRODUCTION

The current environmental context, characterized by climate change, world population increase and the resulting growing demand for food, has created an urgent need for innovative solutions to meet the global requirement of animal production in a sustainable manner. Precision Livestock Farming (PLF) technologies play an essential role in addressing these challenges by maximizing the efficiency and

productivity of livestock production systems [1]. The dairy cattle sector is one of the areas where the effects of climate change are more perceived, mainly due to the increase in global average and peak temperatures and the consequent increase in the herd's sensitivity to heat stress [2]. In this sense, monitoring of the main environmental variables of the farm, represents a task that has been integrated with the traditional livestock farming practices. In this context, PLF technologies have contributed to make viable the application of Information and Communication Technologies, Intelligent Sensors, and Advanced Control Systems for applications in farms.

The close relationship between animal welfare and positive indicators of productivity is a topic addressed by manifold researches in the sector. Several indicators have been developed to quantify the levels of animal discomfort in dairy cattle application, based on environmental variables: Black Globe-Humidity Index (BGHI) [3], Equivalent Temperature Index (ETI) [4], and Temperature-Humidity Index (THI) [5]. According to [6] THI is one of the most widely used indexes in dairy farming applications, due to -among others- the simplicity of its input variables (temperature and relative humidity) as well as its sensitivity of the equation to changes in the input [7]. However, in the great number of the aforementioned studies, the THI obtained corresponds to an average value for the entire indoor area of the livestock building. In the present research, it is proposed to develop a mathematical algorithm that allows the representation in three dimensions of the THI distribution inside of a pilot farm. For this purpose, the measurements of a Smart Monitoring Systems (SMS) will be used as input variables, as well as the potential of the data-driven approach.

II. MATERIALS AND METHODS

A. Case Study

The study focused on a dairy cattle farm located in the metropolitan city of Bologna, Emilia-Romagna, Italy (municipality of Budrio, WGS84 coordinates: 44°33'32.7"N 11°31'09.7"E, 25 m above sea level). The farm served as an experimental site for data collection and parameter monitoring related to the environment, production, and animal behavior. Thanks to a collaboration agreement between the farm and the authors' Department, the research was carried out in cooperation. The dairy cattle barn (Fig. 1) is a rectangular building measuring 50.0 m in length and 27.0 m in width,

featuring a steel frame structure and a double pitched roof made of insulated double sheet steel sandwich panels. Within the barn, approximately 70 Holstein-Friesian lactating cows and 15 dried cows were housed. The internal space was divided into three main areas: storage, feeding, and milking (Automatic Milking System, AMS). The resting area had 78 cubicles with sawdust bedding, separated into two blocks of head-to-head rows in the central part and an additional row running along the length of the storage area.

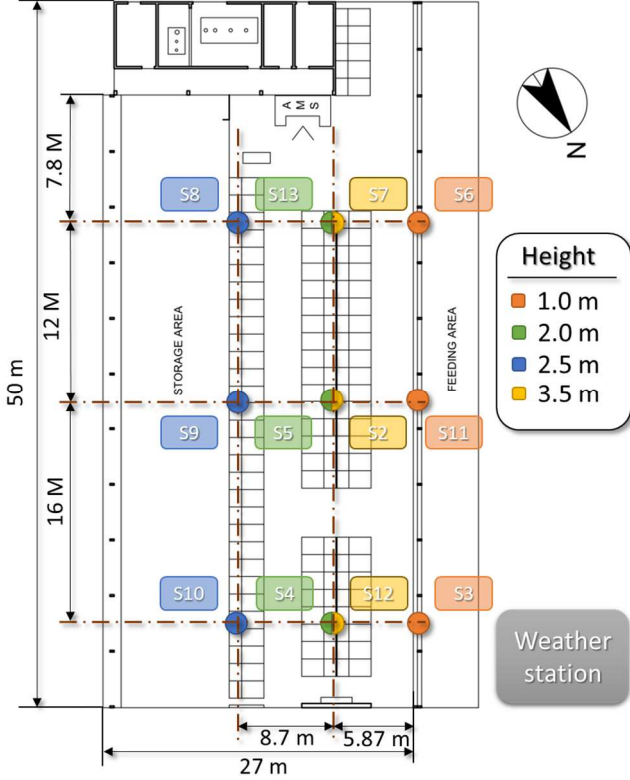


Fig. 1 Plan layout of the barn with the position of the measurement points, indicated by letter S (i.e. sensor) followed by a progressive number. The color indicates the height of the sensor node, according to the legend.

B. Smart Monitoring System

Temperature and relative humidity measurements indoor were recorded using an Smart Monitoring System (SMS) developed in previous research activities [8]. The SMS was composed of 12 sensor nodes strategically placed throughout the barn, together with a weather station outside. These nodes were connected to a gateway via wireless LoRaWAN technology. The placement of the sensor nodes was carefully determined to ensure data collection from significant points within the barn interior, at different heights [9].

C. Data Processing

For the present work, the dataset analyzed corresponds to the period from 8th of June 2022 to the same date to 2023 (364 days). The presence of outliers or missing values is an inherent characteristic of time series, due to, among other factors, the internal precision of the sensors, errors in the communication of the digital systems, as well as noise introduced by the environment of the application context (presence of dust, high humidity values, and even physical damage by the animals).

To provide an accurate analysis, a step of data pre-processing is necessary, by integrating algorithms for the cleaning and the filling of missing values. With respect to the

outlier detection process, three cascading algorithms were used: filtering from the measurement range of the sensor, filtering from the Mean Absolute Deviation algorithm, and finally filtering from the external variables measured by the weather station. Then, a missing value filling algorithm was applied, specifically the Iterative Imputer available in the Python scikit-learn library.

After cleaning the dataset, the calculation the THI calculation was performed following equation (1) developed by [10] where T_{db} ($^{\circ}C$) represent the dry bulb temperature and RH (%) reflect the relative humidity.

$$THI = (1.8T_{db} + 32) - (0.55 - 0.0055RH)(1.8T_{db} - 26.8) \quad (1)$$

In the literature, the heat load according to THI can be categorized into low ($THI \leq 68$), moderate ($68 < THI < 72$) and severe ($THI \geq 72$) stress conditions [11].

D. Interpolation

Interpolation is a critical component in PLF application, where it contributes significantly to effective decision making, inferring unmeasured points. In particular, our application context, the interpolation of the values sampled indoor allowed us to reliably assess the zones of the building where high THI conditions are recognized.

Introduced by [12], Discrete Sibson Interpolation utilizes the discrete Voronoi diagram calculation and improves computational efficiency by exploiting the geometric properties of Sibson's interpolant for a function f evaluated at point p is defined as follows:

$$f(p) = \frac{\sum_{i=1}^k u_i f(p_i)}{\sum_{i=1}^k u_i} = \sum_{i=1}^k \hat{u}_i f(p_i) \quad (2)$$

where:

$$\hat{u}_i = \frac{u_i}{\sum_{i=1}^k u_i}$$

The Python implementation of this algorithm allowed the creation of an interpolation stage using the sample point measurements as input variables, referring to the positions of the sensor nodes as x , y , and z , and providing a point cloud with a volume equal to the farm building size.

III. RESULTS AND DISCUSSION

A. Analyzing heat loads for summer seasons

The time series analysis of the THI values, as depicted in Fig. 2, provides valuable insights into the behavior of this variable throughout different seasons of the year. Notably, a striking similarity in the patterns and trends of the THI values can be observed across the different seasons. Special attention should be given to the summer season, which is highlighted in light orange in the figure. This period stands out as it represents the time when the maximum THI values are reached. The elevated THI values during the summer season indicate potentially challenging thermal conditions within the analyzed environment due to temperatures generally higher in combination with significant humidity, indicating a greater risk of heat stress and discomfort for animals.

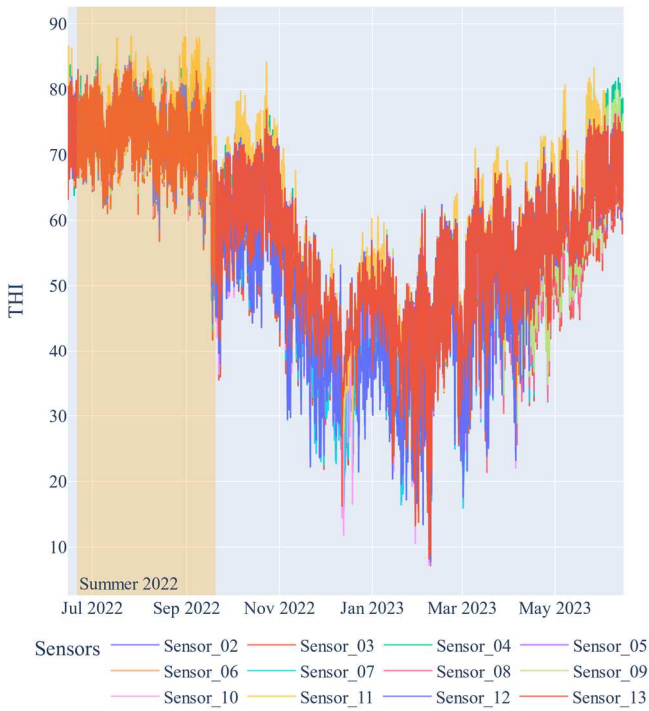


Fig. 2 Time series of Temperature-Humidity Index measured through the sensor nodes of the SMS (summer period highlighted).

A detailed analysis of the summer period is shown in Fig. 3 where -with the exception of the periods corresponding to nights- all the sample points present THI values above the threshold of severe stress condition. This is a critical aspect for the decision-making process in terms of the herds management and the ventilation strategies of the buildings.

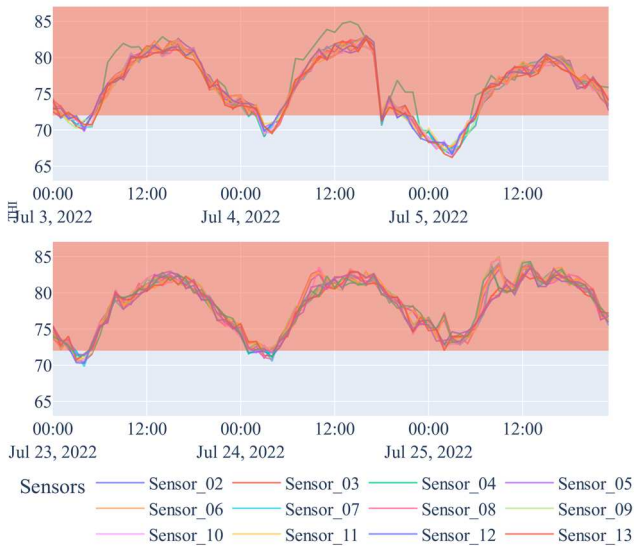


Fig. 3 Details of the time series of Temperature-Humidity Index of the weeks with the highest recorded THI values. Conditions above the threshold of severe heat stress are highlighted in red.

The detection of critical areas with high THI values and their relationship with certain times of the day is a relevant information for farmers, since it allows them to define herd management strategies aimed at avoiding the occurrence of heat stress as well as the accumulation of a large number of animals in the same area because of the heterogeneity of THI and hence the perceived temperature. For this reason, it is essential to know the distribution of the thermal index in the

barn beyond the sample points equipped with nodes of the SMS.

B. 3D Distribution of THI

With the purpose of determining the distribution of thermo-hygrometric conditions throughout the barn volume, an interpolation of the THI values measured by the SMS was performed. Two representative dates of high THI values were selected in order to show significant results of the interpolation and of the estimate of the index in the unmeasured areas. Fig. 4 shows the distribution of THI inside the building with reference to the dates "2022-07-04 16:00" and "2022-07-24 14:00" at the top and bottom, respectively. The similarity of the critical zones with high THI values (S_7), particularly in the center of the southwest end of the building corresponding to the milking area, can be noticed in both dates. This part of the barn hosts the AMS box, hence the increase in the number of animals around this area may have caused a consequent increase in temperature and humidity.

In fact, the time series analysis of interpolation values can provide valuable information about airflow patterns within the barn, aiding in the adjustment of ventilation strategies and the optimization of the spatial distribution of resources for the optimal thermal comfort of dairy cattle. These adjustments can ensure that the thermal comfort needs of the dairy cattle are met uniformly throughout the barn, minimizing heat stress and promoting the overall animal welfare.

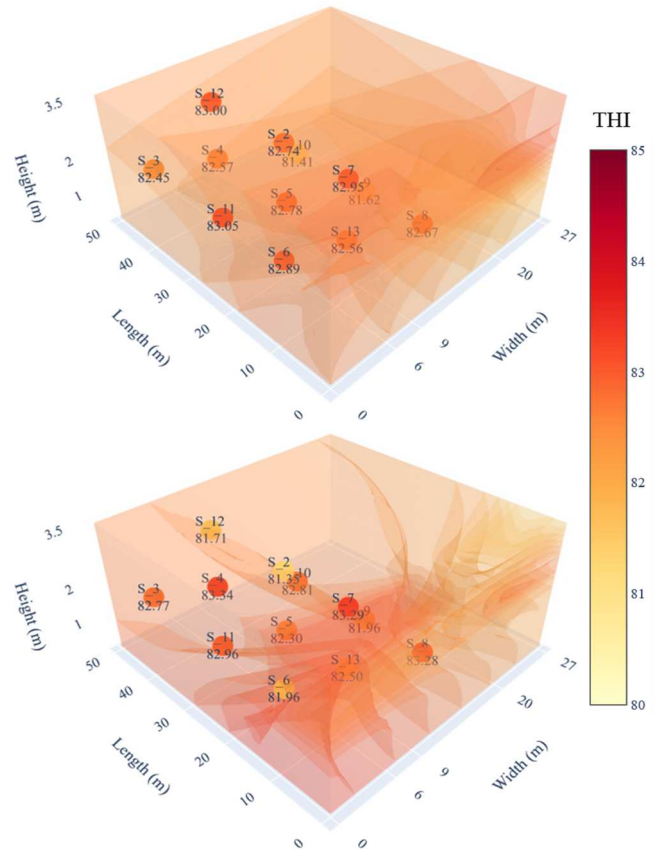


Fig. 4 3D Spatial representation of the indoor THI values with raw sensor position represented by S_2 to S_13: "2022-07-04 16:00" (top) and "2022-07-24 14:00" (bottom).

An effective representation for analyzing the spatial distribution of THI at different levels in the barn can be achieved by extrapolating horizontal sections corresponding to layers of the entire volume covered by data processing. By

setting up four layers and linking each one to a specific height, characterized by the presence of sensors, a comprehensive understanding of the vertical variations in THI can be obtained. This approach allows for a more detailed analysis of how THI varies with height within the barn and to identify potential areas of heat accumulation or areas with more favorable thermal conditions. Due to space limitation, the representation related to the horizontal layers described above is reported hereafter; however, it is possible to further deepen the analysis of the spatial distribution of THI by processing also horizontal sections at different heights, besides cross and longitudinal vertical sections. These results can be obtained by applying the procedure described above and used for the representations presented in this paper.

C. Heatmap Analysis

It is well known that the spatial distribution of environmental variables such as temperature and relative humidity is driven by stochastic phenomena, so it is possible to observe a variability of values at different levels of height.

To provide a more precise analysis, Fig. 5 presents a decomposition of the 3D representation corresponding to a specific date, "2022-07-04".

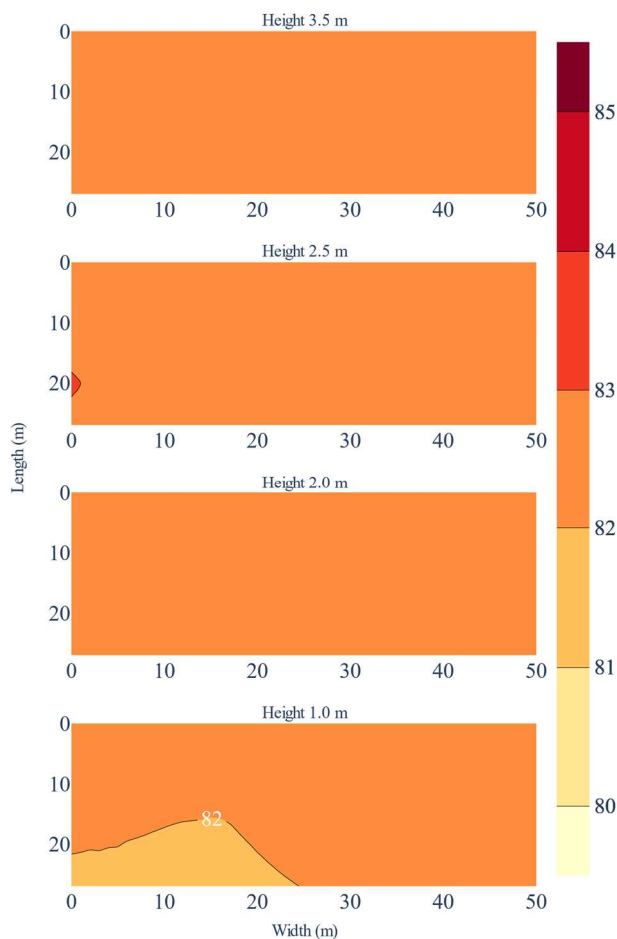


Fig. 5 Heat map of THI indoor values for "2022-07-04 16:00". Origin of the axes in the SW corner of the barn.

The figure includes four layers selected based on the height values of the sensors (3.5 m, 2.5 m, 2.0 m, and 1.0 m). According to the previous analysis, all the internal areas of the barn are experiencing heat stress conditions, indicated by a threshold value of the THI greater than 72. However, it is

worth noting that the layer corresponding to a height of 1.0 m reflects THI values ranging between 81 and 82, which are lower for the zone close to the storage area and the building access. This may be due to variations in airflow from outside, as the storage area contains straw bales that are moved according to the feeding needs of the animals.

On the other hand, the upper layers exhibit a quit uniform distribution of THI, different from the lower layer.

Nonetheless, the analysis of the THI distribution in Fig. 6, referred to 2022-07-04, highlights the variation in THI values across different height levels inside the building.

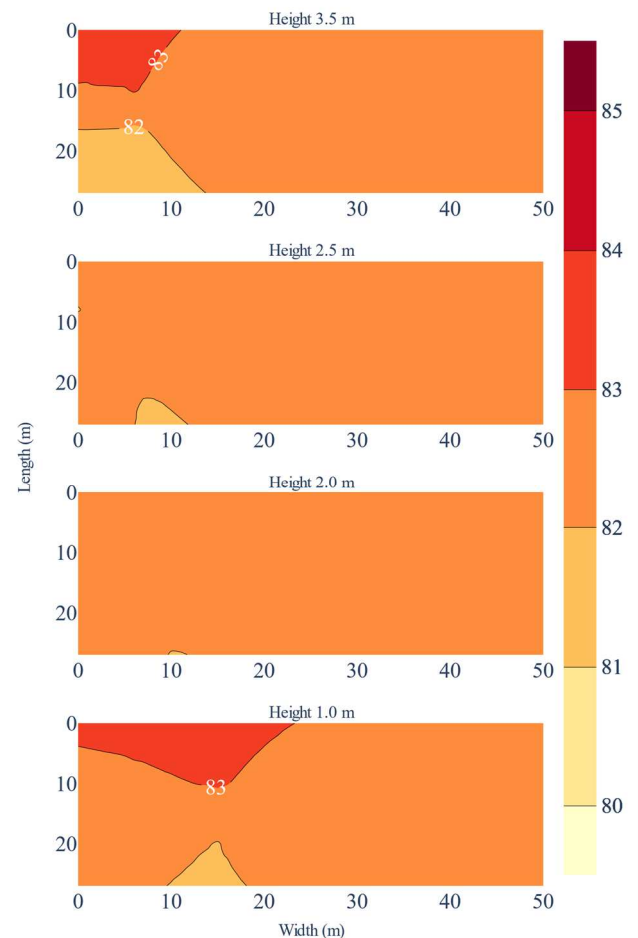


Fig. 6 Heat map of THI indoor values for "2022-07-24 14:00". Origin of the axes in the SW corner of the barn.

The layer corresponding to a height of 1.0 m consistently reflects THI values between 82 and 83 throughout most of its area. There are areas near the South-Eastern side with values lower than 82, which may be related to the previous analysis regarding the increase in flow rate due to the removal of the straw and hay rolls, and the barn access. Nevertheless, there is a zone in the southern part of the feeding area which present significantly higher THI. A similar pattern is reflected in the upper layer at 3.5 m, while the intermediate layers at 2.0 m and 2.5 m remain predominantly in the THI range of 82-83. The segmented analysis further emphasizes the extensive coverage of the severe threshold across most of the internal areas of the farm. However, particular attention should be devoted to the layer corresponding to 1.0 m height, which can be considered as representative of the level of the cows' bodies.

IV. CONCLUSIONS

Overall, the results obtained from the data analysis of the thermo-hygrometric parameters of the studied barn indicates that the THI distribution of indoor farm buildings is not uniform, but rather exhibits spatial inhomogeneities both in horizontal and vertical directions. The variations in THI values at different levels suggest that cows can experience different levels of heat stress in different areas of the barn. This spatial variability highlights the importance of considering also the vertical dimension when assessing the indoor environment and its potential impact on the occupants' comfort and well-being. The patterns observed in the 3D interpolation, and in the consequent decomposition into layers, provide valuable insight into the dynamics of airflow within the building. By analyzing THI values at different heights, it is possible to identify areas of concern that may be prone to higher thermal stress or discomfort. Understanding these patterns can guide decision-making processes related to optimizing cooling and ventilation systems, adjusting temperature controls, or implementing localized measures to improve thermal comfort. In addition, the observed spatial variability in THI values can help identify critical zones within the building. These critical zones may include areas that have consistently high THI values, indicating a higher likelihood of discomfort or even potential health risks for the animals. By pinpointing these zones, appropriate measures such as targeted ventilation or localized cooling can be implemented to mitigate the adverse effects of high thermal stress.

It should be noticed that this work has been carried out on an ordinary commercial farm in the framework of a research agreement. Therefore, the conditions can be considered representative for common situations of livestock barns in the study region. In fact, the analysis methods and the algorithms used have been developed with the purpose of being generally valid in other application contexts.

This study has confirmed the possible presence of critical zones with high THI values beside more temperate ones; thus such zones require the attention by farmers in order to avoid compromising the welfare of the cattle and the consequent reduction in productivity. Among the proposals for possible actions to be taken to improve condition of the farm, the management of the cows' movements in a way that prevents the agglomeration of animals in restricted areas represents an opportunity to be taken. Monitoring and understanding the THI time series data across different seasons allows the farmers to gain insights into the long-term behavior of thermal conditions inside farm buildings. This knowledge can inform decisions on implementing strategies to manage and optimize the indoor climate, such as adjusting ventilation systems, regulating temperature control, or incorporating shading devices to minimize heat accumulation during the summer season.

From the equipment point of view, the relocation of ventilation systems can be effective in order to impact directly on the critical zones previously identified. It is also possible to install new ventilation systems that can either cover a larger cooling area or increase the air flow. Of course, CFD simulations should be performed to optimally design the ventilation system and the results of this study can also provide tools to collect data for the proper validation of numerical models of thermo-fluid dynamics.

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