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Evaluation of microclimate in dairy farms using different model typologies in computational fluid dynamics analyses

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Abstract

Ventilation plays a key role in the livestock buildings since it is important to guarantee a comfortable environment and adequate indoor air quality for the animals. Naturally ventilated barns are usually characterized by high variability in the ventilation conditions. Moreover, the ventilation efficiency can be very different in different areas of a barn because of the different presence of the animals. On the other hand, appropriate ventilation is an essential requirement to ensure animal welfare and efficient and sustainable production since a proper ventilation is the most efficient way to remove undesirable air pollutants and to obtain a comfortable microclimate for the welfare of the animals. In this regard, the computational fluid dynamic (CFD) simulations represent a powerful and useful tool because they can be used to assess ventilation and microclimate conditions. In this context, the present study has the object to assess whether different CFD modelling approaches (i.e. model with animals modelled as obstacles with closed volume and model enriched with cows modelled as obstacles capable of exchanging heat with the surrounding air volume) show differences in relation to the climatic conditions inside a naturally ventilated dairy barn. The comparison of the results, set in terms of indoor air temperature and air velocity contours of the two different models, arises that if a precise definition of the microclimatic features is necessary, in order to correlate them with production parameters or assess animal welfare indexes, thermal simplification is not acceptable since can lead to completely misleading conclusions and incorrect evaluations. Then, only adopting CFD models considering the animal thermal behaviour is possible to obtain effective information both for the proper barn system management and for the creation of useful tools driving the farmers' choices.

Introduction

In livestock buildings, ventilation is an important aspect because it is essential to ensuring a comfortable environment with good indoor air quality (Wang, Pan and Li, 2017; Saha *et al.*, 2020a). According to (Wang, Zhang and Choi, 2018b) and (Ding, Hasemi and Yamada, 2005) ventilation is currently the most effective technique to get rid of unpleasant air pollutants, like dangerous gas and dust, and to create a proper microclimate for the health of the animals. The most crucial indoor environmental features to track in livestock buildings include air temperature, relative humidity, concentration of gases, air velocity, lighting, air pressure, and noise to establish an ideal microclimate (Li, Rong and Zhang, 2016; Rong et al., 2016; Vitali et al., 2021; Chantziaras et al., 2020), particularly in the animal occupied zone (AOZ). According to Choi et al. (Choi *et al.*, 2011), carbon dioxide (CO2), carbon monoxide (CO), ammonia (NH3), methane (CH4), hydrogen sulphide (H2S) and nitrous oxide (N2O) are the undesired gas species that have the greatest impact on the air quality in livestock buildings. Most of these gases are present in the nature air in very low percentages, but if their levels rise above certain thresholds, they can have a negative impact on both housing conditions and animal productivity (Tomasello, Valenti and Cascone, 2019). In buildings for intensive animal husbandry, where proper ventilation is a crucial necessity to guarantee both animal health and effective and sustainable production, these factors are even more crucial. According to available research, air temperature and relative humidity peak values in the hot season of the last five years in central Mediterranean countries (Giannone *et al.*, 2023)were significantly greater than the critical temperature of the thermoneutral zone for several animal species (Gonçalves de Oliveira *et al.*, 2021). Furthermore, if building geometry and management methods are not adequate to minimise the detrimental effects on animals, the indoor conditions could be considerably worse than the outdoor ones in AOZ (Mossad, 2005). These are aspects that proper air quality monitoring systems can help to address. Additionally, it can be highly expensive, both technically and financially, to monitor the air quality throughout the entire layout of a structure with very wide domain. Moreover, because of presence of partitions and interactions with the animals, airflow inside naturally ventilated livestock buildings typically exhibit large variability with time and location inside the barn (Bjerg et al., 2000; Cao et al., 2023).

On the other hand, computational fluid dynamics (CFD) simulations actually represent a powerful tool in this context because they can be used to evaluate the ventilation conditions of specific buildings and to obtain wind-driven solutions for various wind scenarios (D. H. Willits, 2002; Liu, Yang and Niu, 2021; Liu et al., 2008; Wei Liu Mingang Jin & Chen, 2016). Additionally, the numerical models can drive the planning and, when necessary, the evaluation of the best ventilation retrofitting actions.

As with other agriculture buildings (Teitel and Wenger, 2014; Kim, Won and Kim, 2017; Molina-Aiz *et al.*, 2017), the CFD simulations allow for a detailed understanding of both outdoor airflow and wind-driven indoor ventilation flow in a building, computing the features of the interaction between animals and building (King *et al.*, 2017) and providing helpful guidance for the management of openings and shadow curtains (Jackson *et al.*, 2020) for the different seasons.

In this study, a naturally ventilated dairy barn was chosen as case study to analyse and assess the indoor ventilation in different climatic conditions and wind velocity. The CFD simulations have been realized by considering two types of models. A first model has the animals in the barns modelled as obstacles (i.e. simple closed volume). In a second model defined "enriched" the cows have been modelled as volumes also capable of exchanging heat with the surrounding air volume. The comparison between the results of the two different models have allowed to understand the complex ventilation patterns in the building and it provided useful insights for a proper modelling of the animal-structure interaction in livestock buildings also aiming to set the most precise indoor thermal conditions.

Materials and Methods

Description of the case study building

The dairy cattle barn considered in the work is located in the municipality of San Pietro in Casale (Emilia Romagna Region), in a flat countryside in the northern Italy, about 25 km North of Bologna (WGS84 coordinates: 44°42'59.2" N ;11°27'04.9" E, elevation 17.0m a.s.l.). The barn is characterized by a rectangular layout with dimensions of 42.2m × 80.3m (see Figure 1) and has the longitudinal axis (i.e., the longer dimension) SW-NE-oriented (i.e., with -20° azimuth angle). The inner area of the barn serves as the resting place. Closing fences along the symmetry axis enables to divide the herd into two independent groups. The building elevation results in a symmetrical double pitched roof without internal columns and with a ridge line running along the longitudinal axis. It has a continuous ridge opening, a 12.15m ridge height and a roof slope of 33% (see Figure 1). To improve natural transverse ventilation, for both wind-driven and stack effects, the long lateral sides are completely open and only in case of strong wind conditions the animals are protected by using shading nets. Low-pressure, large-droplet water soaker lines, placed above the feeding lanes at a height of 1.80 m from the pavement, provide additional cooling benefits during summer season. The water soaker lines are automatically activated when the indoor temperature, measured by an internal probe placed in the center of the barn at a height of 2.5 m from the pavement, overpasses the 24°C. The water soaker lines alternate 5 minutes of watering and 10 minutes of inactivity. The building hosts about 270 Holstein Friesian cows (70 primiparous and 200 multiparous) milked by four automatic milking systems (AMS), and having average weight of 4.50 kN and average age of 3.5 years. The average daily milk production is 33.3 kg/cow.

Description of the air monitoring system

A customised air quality monitoring system has been tailored and installed in the investigated barn since the available commercial systems were considered not compliant with the requests of the investigation asking for the collection of a very heterogeneous dataset. So, before setting the numerical CFD analyses the activities started with the collection of various indoor and outdoor environmental data. These data have allowed to:

- correlate indoor and outdoor environmental parameters;
- analyse and assess potential correlations between the data of milk production and cow activity with the indoor environmental data;
- continuously monitor the characteristics of the barn housing the animals and assess the welfare

of animals in real time.

The Smart Monitoring System (SMS), depicted in Figure 2, incorporates sensor networks that have been specifically created into a unique system architecture. All the details about the sensors and the architecture of the SMS can be found in (Bovo *et al.*, 2020). The SMS has been designed and construct as a system capable of measuring the main environmental outdoor and indoor data (T, rH, pressure, gases concentration, wind velocity and direction, etc.) and other quantities. It was created to enable the smart control of the facility, to provide a diagnostic of the operating conditions and early alarms in case of anomalies by enabling to capture, to storage, to transmit, and manage massive datasets of physical and environmental features collected in the barn and in its proximity.

Nodes, gateways, and servers are the primary elements of the hardware that make up the monitoring system. Nodes and gateways are installed in the monitored facilities, while servers are physically located at the University of Bologna (Italy). Additionally, the server stores data backup copies on a cloud service to increase data availability and system redundancy. Locally and wirelessly, nodes are linked to the gateway, which gathers data and transmits it to the server. Each node is equipped with on-board sensors or external sensors that can be used to collect one or more of the physical quantities of interest. The node has the capability to interface with the most common commercial sensors.

A small electronic board with limited processing and storage capabilities serves as the node's building block. The board controls battery charging, photovoltaic solar energy harvesting, and the power supply for the entire node and sensors. It is given access to the gateway's wireless transmission capabilities. The gateway, which is an internet-connected device, controls the data reception from the nodes and transmits data to the server. The gateway just serves as a bridge between the cloud server and the nodes' wireless local area network; it has no storage capacity. The gateway needs to be connected to the power grid because of its characteristics. As reported above all the technical details about sensors, probes and the architecture of the SMS can be found in (Bovo *et al.*, 2020) and are not reported here for the sake of brevity of the paper.

Information from the nodes is saved on a workstation that is connected to internet and then made accessible through a web interface by the server. It enables, in real time, chart consultation, dashboard control, and data download to authorized users. Figure 2 shows some details of the SMS installed in the case study building. One node is currently collecting outdoor environmental data, whereas fourteen nodes are gathering indoor data. Temperature, relative humidity (rH), air velocity, and CO_2, CH_4, NH_3, H_2S, and SO_2 concentrations are recorded by the 14 indoor nodes located at height of 2.0 m from the pavement. Temperature, relative humidity, air pressure, wind speed, wind direction, rainfall, and illumination are all measured by the outdoor node. In the present work the data collected by the SMS have been adopted for the validation of the numerical model of the building.

Description of the numerical models

The geometrical 3D model of the barn with the cows positioned inside has been realized with Autodesk Inventor 2020 (Autodesk, 2020) with software license available to the University of Bologna. Then, two different CFD models were developed in parallel. In a first model the cows in the dairy barn have been considered as a simple obstacle (i.e., a closed volume) whereas in a second enriched model, the cows have been modelled as volumes able to exchange heat with the surrounding air volume (for details see Figure 3). In their actual location and true geometry, the inside walls separating corridor from the bedding area have been modelled as impervious obstacles. The Vento AEC (CSPFea, 2015) tool, version 2024, was used to run the simulations. The computational domain, as depicted in Figure 3, is centred on the dairy barn and measures 630 m × 330 m × 60 m. These dimensions have been calculated starting from the building dimensions, with the purpose of including a sufficient surrounding volume to ensure a fully developed flow leeward and windward. In particular, the reference dimension for the domain has been considered the barn height equal to H=12 m at the ridge. Then, the computational volume has characterized by a height 5 H, as well as the distance to the ends ≥10H (upstream and downstream of the building), equal to 24H (Oliveira *et al.*, 2023) (Tominaga *et al.*, 2008). The software uses the Immersed Boundary approach (Huang and Tian, 2019), which makes it possible to quickly and easily build meshes even for complex geometries (Tu, Yeoh and Liu, 2012). In fact, in this method, a simulation is run on a grid that does not conform to the boundary surface, and the immersed boundary is represented by the surface mesh itself. The simulations have been conducted under steady state, incompressible and turbulent regime. In the CFD simulations, the classic k-e turbulence model(Wu *et al.*, 2012; Wang *et al.*, 2021) (Launder and Spalding, 1983) has been applied to the turbulent transport problem considering its reliable and its extensive validation in several applications (Blanes-Vidal *et al.*, 2008; Norton *et al.*, 2009). Then, using Einstein's summation notation, the mass conservation in Eq.(1), the momentum conservation in Eq.(2), the energy conservation in Eq.(3), with the Boussinesq approximation, are (Guillermo De la Torre-Gea *et al.*, 2011):

$$\frac{\Delta U_i}{\Delta x_i} = 0 \tag{1}$$

$$\rho U_j \frac{\delta U_i}{\delta x_i} = -\frac{\Delta P}{\Delta x_i} + \frac{\delta}{\delta x_i}\left[(\mu + \mu_t)\frac{\delta U_i}{\delta x_j}\right] + f_b + S_j \tag{2}$$

$$\rho C \frac{DT}{Dt} = k\,\nabla^2 T \tag{3}$$

where: U_j is the velocity components [m s^{-1}], x_i is the spatial coordinate [m], P is the pressure [Pa], ρ is the air density [kg m^{-3}], μ is air viscosity [m^2 s^{-1}], and μ is turbulent (eddy) viscosity [m^2 s^{-1}]. Moreover, S_j is a source term, f_b is a vector which represents the body forces, C is the specific heat, T(x,t) [K] is the temperature field and k is the thermal conductivity coefficient.

Then, the turbulence equations are reported for the selected k-ε turbulence model, in Eq.(4a) and Eq.(4b).

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{4a}$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_i}(\rho \varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \tag{4b}$$

where: k is turbulent kinetic energy [$m^2 \, s^{-2}$], ε is turbulent kinetic energy dissipation [$m^2 \, s^{-3}$], G_k represents the contribution of velocity gradients to turbulence kinetic energy, G_b is contribution to turbulence kinetic energy of buoyancy, and the various constants have been assumed equal to σ_k =1.0, σ_ε =1.3, $C_{1\varepsilon}$ =1.44 and $C_{2\varepsilon} = 1.92$ as suggested in (Richards and Hoxey, 1993). For the convergence process, a *fully implicit Gauss Seidel* solution algorithm is provided to solve the linear system of equations obtaining an efficient numerical convergence and the convergence criteria have been defined for a threshold value equal to 10^{-5} for all field variables.

Each cow has been modelled as a 3D equivalent and simplified parallelepiped volume(Mondaca and Choi, 2016) with dimensions derived from (Bartali, 1999), in order to reduce computational time and avoid high skewness elements (Bustos-Vanegas *et al.*, 2019). In the model, the animal occupied zone (AOZ) has been filled with randomly arranged 270 simplified cows' geometry model (CM), instead of equivalent porous medium model (PMM) (Norton *et al.*, 2010; Doumbia *et al.*, 2021).

Moreover, a logarithmic trend has been assumed for the wind profile, considering the literature studies (Norton *et al.*, 2010; Rong *et al.*, 2015; Bovo *et al.*, 2022). The related equations for wind profile (see Eq.(5)), turbulent kinetic energy (see Eq.(6)) and turbulent dissipation rate (Eq.(7)) are:

$$U(z) = \frac{u_*}{\kappa}\ln\left(\frac{z + z_0}{z_0}\right) \tag{5}$$

$$k = \frac{u_*^2}{\sqrt{C_\mu}} \tag{6}$$

$$\varepsilon = \frac{u_*^3}{k\sqrt{z - z_0}} \tag{7}$$

where: U(z) is the horizontal velocity [m/s], u_* is the friction wind velocity has been derived from SMS collected data, *k* is the von Karman's constant (assumed equal to 0.41), z is the height above the ground and z_0 is the surface roughness (assumed equal to 0.01 for open grassland), C_μ is a coefficient used to define the eddy viscosity in the models and was assumed equal to 0.09. No slip wall boundary condition was applied to all the walls in the domain.

As discussed in the previous section, in the work two different modelling approaches have been considered for the cows. In fact, in the simplified model (labelled with an "S" in the following) the cows have been simulated as closed volume without any thermal interaction with the surrounding environment. On the other hand, the enriched model (labelled with a "E" in the following) has been carried out considering the cows, not only as geometrical volume, but also as heat sources able to thermally interact with the surrounding environment so simulating the thermoregulatory processes of the cows allowing them to maintain a constant body temperature. The comparison between the two different modelling strategies has the goal to quantify the possible errors in the estimation of the indoor climate features of interest introduced by a too simplified modelling strategy; then it aims at establishing in which cases a simplified model can provide reliable information for the cow welfare assessment.

The heat flux produced by a single cow, has been calculated based on the simplified relation reported in Eq. (8):

$$H = 6.6 \cdot m^{0.75} \tag{8}$$

where: m is the mass of the animal [kg] and H is the heat emission [W]. The average mass for a representative cow in the herd has been assumed equal to 450 kg, and then a heat flux equal 73.1 W/m^2 was considered in the simulations. The heat flux has been considered involving the whole surface of the simplified modelled standing cows and has been assumed constant in the analysis since the investigated temperatures have ranged in the thermal neutrality zone of the animals (Bartali, 1999).

For both the models, simplified and enriched, the grid convergence study has been realized using four different structural meshes. The meshes were gradually refined, in particular progressively reducing the cell sizes in the AOZ areas and close to the envelope walls, in four different grids, from 6×10^6 cells to 16×10^6 cells.

Five different (horizontal) air velocity profiles outcoming from the simulation results and encompassing the entire domain, were considered for the grid convergence analysis. Two velocity profiles were chosen near the building, while the other three were chosen by intersecting the building on three different levels. Through the calculation of the infinity norm, as shown in Eq. (9), going from the coarsest to the finest mesh, these air velocity (v) profiles have been utilised to assess how the results vary with the mesh refinement:

$$||v||_{inf} = max|v_a - v_b| \tag{9}$$

where: *a* refers to the single air velocity vector of the finer mesh and *b* refers to the single air velocity vector of the coarser mesh. As an example, the main result of the grid convergence study for the model with cows able to exchange heat are illustrated in Figure 4 in terms of average infinity norm on the five profiles of the horizontal air velocity. The average of the infinity norm, resulting from the comparison of each profile considered, has been calculated, allowing to define the proper grid dimension. The mesh with 8×10^6 cells has been selected for the analyses of the two models.

Ventilation scenarios

The analysis of the weather data, collected for three years by the outdoor node of the farm, has allowed the definition of the most frequent ventilation conditions (in terms of wind velocity and wind direction) for winter and summer seasons. The data collected in Table 1, are associated to characteristic temperatures of winter and summer seasons (where C: cold refers to the winter season and H: hot refers to the summer season) for two different wind intensities (LV: low velocity; HV: high velocity). The wind reference velocity has been used to derive the friction velocity value of the external wind velocity profile for the CFD simulations (see eq. 5).

So, four ventilation scenarios have been analysed via CFD simulations: two representatives of the winter season and two for the summer season differentiated by two wind velocities. The ventilation scenarios of the winter season have been defined for simplicity "cold scenarios". Whereas the ventilation scenarios simulating the conditions during two representative days in summer season have been defined for simplicity "hot scenarios".

For the assessment of the accuracy of the models, the comparison between the in-field measurements of the horizontal air velocity, collected at 2.5m by the anemometer sensors of the SMS, with the results provided by the models for the four different scenarios, have been set. The measures adopted for the estimation of the errors have been the Maximum Absolute Difference (MAD) and the Root Mean Square Error (RMSE).

Climate conditions and relation with animal welfare and animal production

Several papers have investigated the relation between environmental conditions and one or more animal-based indicators with the main object of modelling short- or long- term effects of heat stress or detect poor welfare conditions. In the most of these works, the environmental conditions have been modelled by the Temperature-Humidity Index (THI) in the barn (Carabaño *et al.*, 2016; Pinto *et al.*, 2020; Giannone *et al.*, 2023) or indices derived by the THI, like the Heat Load Index (HLI), developed mainly for animals raised outdoors and considering also air velocity and solar radiation values (Heinicke *et al.*, 2019, 2021; Tresoldi, Schütz and Tucker, 2019). Other authors have considered alternative measures such as the Black Globe Humidity Index (BGHI) or Comprehensive Climate Index (CCI). Within the literature, it appears that Temperature-Humidity Index (THI) is the most commonly utilized index, despite not fully representing the thermal conditions (Garcia *et al.*, 2023). The THI expression considered in the paper is the one indicated by the National Research Council (National Research Council, 1971):

$$\mathrm{THI} = [(1.8 \times T_{db} + 32) - (0.55 - (0.0055 \times RH) \times (1.8 \times T_{db} - 26)] \quad (10)$$

where T_{db} is the air dry bulb temperature (°C) and RH is the air relative humidity (%).

In the calculation of the THI value the air temperature is the most influential feature. So, in the following THI values will be considered as an indicator for the effects of heat stress, in lieu of knowing the internal body temperature of animals. Following the Eq. (10) the achieving of different threshold values indicates different stress level. For example, following the values reported in (National Research Council, 1971) for dairy cows, THI values > 72 indicate slight stress level, THI > 78 indicates a moderate stress level, THI > 88 indicates conditions of serious stress and for value of THI > 98 dangerous level with high risk of death for animals. For THI ≤ 72 the climate conditions do not induce heat stress on the cows (Bernabucci *et al.*, 2014; Berman *et al.*, 2016; Carabaño *et al.*, 2016; Moretti *et al.*, 2017; Ji *et al.*, 2020; Müschner-Siemens *et al.*, 2020). Furthermore, the THI value is used for the assessment of the possible drop in the production associated to heat stress conditions (Bovo et al., 2021).

Results and Discussion

Model validation with in-field measurements

The model validation has been performed on the model with heat exchange from animals, since it has a greater degree of complexity and also takes into account the presence of the animals inside barn, reflecting the actual conditions of the experimental in-field scenario, where the environmental data are collected. The numerical results have been compared with those in the same points, from the database collected by the SMS in a particular moment characterized by climatic conditions similar to those of the simulation (see Table 1).

From the comparison between the in-field measurements of horizontal air velocity, collected at 2.5m by the anemometer sensors of the SMS, with the results provided by the models for the four different scenarios, have returned the Maximum Absolute Difference (MAD) and the Root Mean Square Error (RMSE) values summarized in Table 2 for each scenario.

It is worth noting that, according to (Zhao Zhang Wei Zhang and Chen, 2007), a good agreement is present, when the error measure is less than 10% of the average measure, and agreement is acceptable when the ratio goes from 10% and 30%, marginal when the ratio is between 30% and 50%, and poor when ratio is greater than 50%. If we consider this criterion, it is possible to conclude that the model has acceptable agreement with measured data and can be considered reliable for the purposes of the study

Air flow patterns

The air vector velocity contour resulting of the two models, enriched and simplified, is illustrated in Figure 5. The two models show completely different ventilation patterns comparing the CLV (cold with low velocity) with the HLV (hot with low velocity) scenarios.

In fact, for the simplified model (see Figure 5 a., b., c., and d.), the natural ventilation is recognizable with a cross ventilation air flow pattern, with inlet air entering from left side and outlet mainly from right side and only partially from the roof openings, with very low velocity magnitudes about 0.05 m/s. Instead, in case of enriched model (see Figure 5 e., f., g., and h.), the presence of expected chimney effect is clearly visible, with bottom-up air circulation, inlet from lateral openings and moving to the roof openings. In the enriched model, the addition of the thermal behaviour of the animals significantly modifies the indoor air velocity contour and provides a magnitude in the range between 0.06 to 0.44 m/s. In Figure 5d., e., g., h., characterized by high wind velocity, both cold and hot weather, the results do not show significant differences in terms indoor air flow patterns and velocity magnitude comparing enriched and simplified model.

However, in Figure 6, some slight variations on the velocity magnitude can be observed for the HV cases in the animal occupied zone (AOZ). In fact, the heat produced by the animals influences the velocities in the AOZ, rising magnitudes, represented by a wider green area closed to the modelled animals. This affects positively the natural ventilations on the area. Moreover, for the LV cases, Figure 6 highlights the chimney effect occurring in case of thermal contribution of animals and the airflow distribution and velocities in the AOZ. It is evident that the indoor air flow moves from the bottom to the top and exits by the leeward right opening.

Then, in terms of velocity magnitude values, the simplified model gives reliable results only in case of high wind velocity, with cross ventilation effect that plays the main role in the natural ventilation efficiency of the building. In fact, in a wind dominated regime, other studies about natural ventilation efficiency have been modelling the structure without internal heat sources or with a simplified model related to occupants (i,e. cattle, pigs) (Norton *et al.*, 2010; Bustos-Vanegas *et al.*, 2019; Saha *et al.*, 2020b; Doumbia *et al.*, 2021; Xin *et al.*, 2022). In fact, some authors performed CFD simulations with a validated model, which provided useful information on airflow characteristics at cow height, using similar methodology and model, only in case of wind driven ventilation (Saha *et al.*, 2020b).

However, this approach could lead to less precise results, especially if the area of investigation of major interest is the AOZ (Doumbia *et al.*, 2021). This aspect is of fundamental importance because in naturally ventilated livestock buildings, only a precise definition of air flows and air speed patterns allows the proper evaluation of the air exchanges necessary to guarantee the healthiness of the air in which the animals are housed. Moreover, in the hot season, the indoor air velocity can have an important influence on the mitigation of heat stress problem and so, the precise calculation of the velocity patterns is a fundamental requisite for the proper assessment of the thermal comfort in the barn. Moreover, in other works, see (Wang, Zhang and Choi, 2018a), the authors focused on this important aspect of CFD modelling, thanks to a method to analyse the heat-transfer, underlined the fact that the airflow speed has a positive effect on the convective heat-transfer of a cow, independently from its position. In particular, from the results obtained, it was clear that the airflow in AOZ should be increased as much as possible, to ensure cooling effect on cows under hot conditions.

Indoor temperature assessment

As discussed in a previous section, another important feature for the judgement of the quality and suitability of the microclimate conditions in which cows are housed, is the indoor air temperature. Figure 7 shows for the first 4 meters of height of the barn, the contour of the differences between indoor temperature provided by enriched model and simplified model for the four investigated scenarios. With reference to the area occupied by the cows for most of the time, i.e., the resting area, it is wort to note as for the scenarios HLV and CLV the error in the temperature assessment spans from about 2°C to peak values of 7°C, with an average value of about 4°C. From the Eq.(10), assuming an average relative humidity value of 75% as recorded by the SMS, the estimation of the THI in the barn for the HLV scenario is affected by a non-negligible error of 4-5 points. In fact, the correct value of THI equal to 77 is considerably underestimated, leading to the erroneous conclusion that the animals are not in conditions of heat stress (THI ≤ 72).

Similar conclusions can be draft for the scenario CHV with temperature error ranging from 2°C to 10°C and average value about 5°C in correspondence of the AOZ. This brings to an error on the THI even higher than previous case with expected consequences potentially more dangerous for the animal health. In this case in fact, the underestimation of the THI can reach, assuming a relative humidity value of 75%, peak values of 9-10 points (i.e. 73 points instead of the correct 82 points).

It is worth to note that this inaccurate assessment of the temperature in the AOZ has important consequences also in the estimation of the drop production induced by not adequate indoor climate conditions as in case of heat stress. For example, using the well-known relations provided in (Baêta *et al.*, 1987), if we assume the HLV scenario, for a relative humidity value of 75% and a temperature of 24°C, it is expected a production decrease of about 5%. Instead, by considering the correct temperature values, ranging from 26°C and 31°C the production decrease goes from 10% to 30%, values much more similar to those that are usually found in the literature and confirmed by interviews the authors had with the local farmers. So, as expected, the adoption of a poor thermodynamic model provides results also in terms of animal welfare and animal production very different from those actually measured in the farm and can lead to completely misleading evaluations and incorrect conclusions.

So, in the context of the simulation and prediction of micro climate of livestock buildings, models that do not consider the thermodynamic interaction between animals and the surrounding environment could be acceptable only if a rough estimate of the features that characterize microclimatic conditions, with relation particularly with air speed and temperature, is needed. On the opposite, if the objective of numerical simulations is to precisely define microclimatic conditions, in order to correlate them with production parameters or assess indicators for animal welfare assessment, such simplification is not acceptable. In addition, simulations that consider the enriched model do not require much more computational effort than those performed on the simpler models. In particular, in this case it is possible thanks to the immersed boundary methods which allows to reduce the costly meshing process, and the issues related to large deforming grids. This method contributes to enhanced computational efficiency by simplifying domain composition and load balancing in parallel processing within a Cartesian mesh framework. In fact, for the resolution of the simulations of this work, the authors recorded an increase, ranging from 10% to 15%, of the computational time necessary to solve the analysis until convergence, which goes from 16-17 sec to 20-21 sec for iteration.

Finally, if we consider that solutions provided by fluid dynamic models are becoming increasingly used as tools for the management of barn systems or for the generation of alerts in automation processes or in decision-support to farmers' choices, it is authors' opinion that the simulation models adopted for these purposes cannot be the simplest ones but must be the enriched models. All this, in order to ensure adequate welfare for the animals, helps to achieve the highest levels of production, make the optimal use of the systems in the barn in order to increase the overall sustainability of the sector.

Although the results reported here are very encouraging and confirm that CFD analyses are a useful and reliable tool, further improvements are still to be desired. In fact, future lines of research will have to improve the calibration of biological models of animals in order to estimate more precisely the interaction between animals and the environment. In addition, the study of a larger number of case studies will allow to evaluate the applicability of these analyses also to other livestock buildings and in other ventilation scenarios so to obtain more general outcomes. On the other hand, the possibility of introducing sources of gaseous emissions into the models will make it possible to estimate the microclimatic conditions in the barn, also considering the concentrations of undesired gases in the areas occupied by the animals.

Conclusions

In this study, the main microclimate features in a naturally ventilated dairy barn hosted dairy cows have been numerically investigated by comparing two different modelling approaches: in a first model the animals are modelled as obstacles with closed volume elements, whereas in a second enriched model, the cows were introduced as obstacles with volume able to exchange heat with the surrounding air. The main conclusions of the paper can be summarized as in the following:

- the two model classes showed in general very different values of indoor air velocity and the simplified model gives reliable results only in case of high wind velocity, when the cross-ventilation effect plays the main role in the natural ventilation of the building;
- anyway, in general, the adoption of the simplified model brings to a less precise assessment of the indoor air velocity values, especially in the area occupied by the animals of major interest.
- with reference to the air temperature assessment, in the resting area, in case of low wind velocity, the error in the temperature spans from 2°C to 7°C, with an average value of about 4°C. Instead, in case of high wind velocity, the temperature error ranges from 2°C to 10°C with average value of about 5°C. The inaccurate estimation of the temperature range in the area occupied by the animals, can provide non-negligible error of underestimation of the THI in the barn, all this leading to the erroneous conclusion related to animal welfare and milk production trends;
- simulations that consider enriched model showed an increase of the computational time necessary to solve the analysis until convergence ranging from 10% to 15%, so not considerable.

For these reasons, it is authors' opinion that the models adopted for purposes of animal welfare assessment or animal productions forecast or again driving decision-support systems, cannot be the simplest ones but must be the enriched models. In general, despite several papers in literature make use of models that do not consider the thermodynamic interaction between animals and surrounding environment, this simplification seems not justifiable if the focus is the thermal comfort of housed animals.

This work represents the first attempt to provide useful guidelines for a proper modelling of buildings for livestock and further analyses, modelling improvements and applications to other case studies will be necessary, in order to create a more robust frame driving the modelling choices of researchers, software developers and developers of tools for farmers. Future works must improve the biological behaviour of animals in order to estimate more precisely the interaction with the environment and in addition, the study of a larger number of case studies will allow to evaluate the applicability of these analyses also to other livestock buildings and in other ventilation scenarios so to obtain general outcomes useful in a wider range of applications.

References

Autodesk (2020) *No Title*, *'Inventor'*. Available at: https://www.autodesk.it/products/inventor%0A.

Baêta, F. *et al.* (1987) 'Equivalent temperature index at temperatures above the thermoneutral for lactating dairy cows', in. Available at: https://api.semanticscholar.org/CorpusID:131242713.

Bartali, E.H. (1999) *Volume II. Animal Production & Aquaculture Engineering*, *CIGR Handbook of Agricultural Engineering*.

Berman, A. *et al.* (2016) 'A comparison of THI indices leads to a sensible heat-based heat stress index for shaded cattle that aligns temperature and humidity stress', *International Journal of Biometeorology*, 60(10), pp. 1453–1462. Available at: https://doi.org/10.1007/S00484-016-1136-9.

Bernabucci, U. *et al.* (2014) 'The effects of heat stress in Italian Holstein dairy cattle', *Journal of Dairy Science*, 97(1), pp. 471–486. Available at: https://doi.org/10.3168/jds.2013-6611.

Bjerg, B *et al.* (2000) 'The Effects of Pen Partitions and Thermal Pig Simulators on Air flow in a Livestock Test Room', *Journal of Agricultural Engineering Research*, 77(3), pp. 317–326. Available at: https://doi.org/10.1006/jaer.2000.0596.

Bjerg, B. *et al.* (2000) 'The effects of pen partitions and thermal pig simulators on airflow in a livestock test room', *Journal of Agricultural and Engineering Research*, 77(3), pp. 317–326. Available at: https://doi.org/10.1006/jaer.2000.0596.

Blanes-Vidal, V. *et al.* (2008) 'Application of computational fluid dynamics to the prediction of airflow in a mechanically ventilated commercial poultry building', *Biosystems Engineering*, 100(1), pp. 105–116. Available at: https://doi.org/10.1016/j.biosystemseng.2008.02.004.

Bovo, M. *et al.* (2020) 'A Smart Monitoring System for a Future Smarter Dairy Farming', in *2020 IEEE International Workshop on Metrology for Agriculture and Forestry, MetroAgriFor 2020 - Proceedings*, pp. 165 – 169. Available at: https://doi.org/10.1109/MetroAgriFor50201.2020.9277547.

Bovo, M. *et al.* (2021) 'Random Forest Modelling of Milk Yield of Dairy Cows under Heat Stress Conditions', *Animals*, 11(5). Available at: https://doi.org/10.3390/ani11051305.

Bovo, M. *et al.* (2022) 'Assessment of geometrical and seasonal effects on the natural ventilation of a pig barn using CFD simulations', *Computers and Electronics in Agriculture*, 193(September 2021), p. 106652. Available at: https://doi.org/10.1016/j.compag.2021.106652.

Bustos-Vanegas, J.D. *et al.* (2019) 'Numerical simulation of airflow in animal occupied zones in a dairy cattle building', *Biosystems Engineering*, 186, pp. 100–105. Available at: https://doi.org/10.1016/j.biosystemseng.2019.07.002.

Cao, M. *et al.* (2023) 'Predicting Ventilation Rate in a Naturally Ventilated Dairy Barn in Wind-Forced Conditions Using Machine Learning Techniques', *Agriculture*, 13(4). Available at: https://doi.org/10.3390/agriculture13040837.

Carabaño, M.J. *et al.* (2016) 'Modeling heat stress under different environmental conditions', *Journal* *of Dairy Science*, 99(5), pp. 3798–3814. Available at: https://doi.org/10.3168/jds.2015-10212.

Choi, H.L. *et al.* (2011) 'The Correlation between Thermal and Noxious Gas Environments, Pig Productivity and Behavioral Responses of Growing Pigs', *International Journal of Environmental Research and Public Health*, 8(9), pp. 3514–3527. Available at: https://doi.org/10.3390/ijerph8093514.

CSPFea (2015) 'VENTO , different CFD'.

D. H. Willits (2002) 'The Effect of Shade Cloth Temperature on the Cooling Efficiency of Shade Cloths in Greenhouses', in *2002 Chicago, IL July 28-31, 2002*. St. Joseph, MI: American Society of Agricultural and Biological Engineers. Available at: https://doi.org/10.13031/2013.9540.

Ding, W., Hasemi, Y. and Yamada, T. (2005) 'Natural ventilation performance of a double-skin facade with a solar chimney', *Energy and Buildings*, 37(4), pp. 411–418. Available at: https://doi.org/http://dx.doi.org/10.1016/j.enbuild.2004.08.002.

Doumbia, E.M. *et al.* (2021) 'CFD modelling of an animal occupied zone using an anisotropic porous medium model with velocity depended resistance parameters', *Computers and Electronics in Agriculture*, 181, p. 105950. Available at: https://doi.org/10.1016/j.compag.2020.105950.

Garcia, C.A.P. *et al.* (2023) '3D numerical modelling of temperature and humidity index distribution in livestock structures: a cattle-barn case study', *Journal of Agricultural Engineering*, 54(3). Available at: https://doi.org/10.4081/jae.2023.1522.

Giannone, C. *et al.* (2023) 'Review of the Heat Stress-Induced Responses in Dairy Cattle', *Animals*, 13(22). Available at: https://doi.org/10.3390/ani13223451.

Gonçalves de Oliveira, D.C. *et al.* (2021) 'Modeling of the thermal performance of piglet house with non-conventional floor system', *Journal of Building Engineering*, 35, p. 102071. Available at: https://doi.org/10.1016/j.jobe.2020.102071.

Guillermo De la Torre-Gea *et al.* (2011) 'Computational fluid dynamics in greenhouses: A review', *African Journal of Biotechnology*, 10, pp. 17651–17662.

Heinicke, J. *et al.* (2019) 'Cow individual activity response to the accumulation of heat load duration', *Journal of Thermal Biology* [Preprint]. Available at: https://doi.org/10.1016/j.jtherbio.2019.03.011.

Heinicke, J. *et al.* (2021) 'Heat Load-Induced Changes in Lying Behavior and Lying Cubicle Occupancy of Lactating Dairy Cows in a Naturally Ventilated Barn', *Annals of Animal Science*, 21(4), pp. 1543–1553. Available at: https://doi.org/10.2478/aoas-2020-0113.

Huang, W.-X. and Tian, F.-B. (2019) 'Recent trends and progress in the immersed boundary method', *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 233(23–24), pp. 7617–7636. Available at:

https://doi.org/10.1177/0954406219842606.

Jackson, P. *et al.* (2020) 'Using CFD Modelling to Relate Pig Lying Locations to Environmental Variability in Finishing Pens', *Sustainability*, 12, pp. 1–16. Available at: https://doi.org/10.3390/su12051928.

Ji, B. *et al.* (2020) 'A review of measuring, assessing and mitigating heat stress in dairy cattle', *Biosystems Engineering*, 199, pp. 4–26. Available at: https://doi.org/https://doi.org/10.1016/j.biosystemseng.2020.07.009.

Ji, B. *et al.* (2022) 'A machine learning framework to predict the next month's daily milk yield, milk composition and milking frequency for cows in a robotic dairy farm', *Biosystems Engineering*, 216, pp. 186–197. Available at: https://doi.org/https://doi.org/10.1016/j.biosystemseng.2022.02.013.

Kim, M., Won, W. and Kim, J. (2017) 'Integration of carbon capture and sequestration and renewable resource technologies for sustainable energy supply in the transportation sector', *Energy Conversion and Management*, 143, pp. 227–240. Available at: https://doi.org/10.1016/j.enconman.2017.04.010.

King, M. *et al.* (2017) 'Investigating the in fl uence of neighbouring structures on natural ventilation potential of a full-scale cubical building using time-dependent CFD', *Journal of Wind Engineering & Industrial Aerodynamics*, 169(March), pp. 265–279. Available at: https://doi.org/10.1016/j.jweia.2017.07.020.

Launder, B.E. and Spalding, D.B. (1983) 'The Numerical Computation of Turbulent Flows', in *Numerical Prediction of Flow, Heat Transfer, Turbulence and Combustion*. Elsevier, pp. 96–116. Available at: https://doi.org/10.1016/b978-0-08-030937-8.50016-7.

Li, H., Rong, L. and Zhang, G. (2016) 'Study on convective heat transfer from pig models by CFD in a virtual wind tunnel', *Computers and Electronics in Agriculture*, 123, pp. 203–210. Available at: https://doi.org/10.1016/j.compag.2016.02.027.

Liu, X., Yang, L. and Niu, S. (2021) 'Research on the effect of different position on classroom ventilation in a "L" type teaching building', *Journal of Building Engineering*, 33, p. 101852. Available at: https://doi.org/10.1016/j.jobe.2020.101852.

Marumo, J.L. *et al.* (2022) 'Influence of environmental factors and parity on milk yield dynamics in barn-housed dairy cattle', *Journal of Dairy Science*, 105(2), pp. 1225–1241. Available at: https://doi.org/10.3168/jds.2021-20698.

Molina-Aiz, F.D. *et al.* (2017) 'Using computational fluid dynamics to analyse the CO2 transfer in naturally ventilated greenhouses', in *Acta Horticulturae*. Available at: https://doi.org/10.17660/ActaHortic.2017.1182.34.

Mondaca, M. and Choi, C.Y. (2016) ‘An evaluation of simplifying assumptions in dairy cow computational fluid dynamics models’, *Transactions of the ASABE*, 59(6), pp. 1575 – 1584. Available at: https://doi.org/10.13031/trans.59.11908.

Moretti, R. *et al.* (2017) ‘Heat stress effects on Holstein dairy cows’ rumination’, *Animal*, 11(12), pp. 2320–2325. Available at: https://doi.org/10.1017/S1751731117001173.

Mossad, R.R. (2005) ‘OPTIMIZATION OF THE VENTILATION SYSTEM FOR A FORCED VENTILATION PIGGERY’, *Journal of Green Building*, 4(4), pp. 113–133.

Müschner-Siemens, T. *et al.* (2020) ‘Daily rumination time of lactating dairy cows under heat stress conditions’, *Journal of Thermal Biology*, 88. Available at: https://doi.org/10.1016/j.jtherbio.2019.102484.

National Research Council (1971) *A Guide to Environmental Research on Animals*. Washington, DC: The National Academies Press. Available at: https://doi.org/10.17226/20608.

Norton, T. *et al.* (2009) ‘Assessing the ventilation effectiveness of naturally ventilated livestock buildings under wind dominated conditions using computational fluid dynamics’, *Biosystems Engineering*, 103(1), pp. 78–99. Available at: https://doi.org/10.1016/j.biosystemseng.2009.02.007.

Norton, T. *et al.* (2010) ‘Optimising the ventilation configuration of naturally ventilated livestock buildings for improved indoor environmental homogeneity’, *Building and Environment*, 45(4), pp. 983–995. Available at: https://doi.org/10.1016/j.buildenv.2009.10.005.

Oliveira, C.E.A. *et al.* (2023) ‘Analysis of Heat and Mass Transfer in Compost-Bedded Pack Barns for Dairy Cows Using Computational Fluid Dynamics: A Review’, *Applied Sciences (Switzerland)*, 13(16). Available at: https://doi.org/10.3390/app13169331.

Pinto, S. *et al.* (2020) ‘Critical THI thresholds based on the physiological parameters of lactating dairy cows’, *Journal of Thermal Biology*, 88. Available at: https://doi.org/10.1016/j.jtherbio.2020.102523.

Richards, P.J. and Hoxey, R.P. (1993) ‘Appropriate boundary conditions for computational wind engineering models using the k-ϵ turbulence model’, *Journal of Wind Engineering and Industrial Aerodynamics*, 46–47, pp. 145–153. Available at: https://doi.org/https://doi.org/10.1016/0167-6105(93)90124-7.

Rong, L. *et al.* (2015) ‘The effect of wind speed and direction and surrounding maize on hybrid ventilation in a dairy cow building in Denmark’, *Energy and Buildings*, 86, pp. 25–34. Available at: https://doi.org/10.1016/j.enbuild.2014.10.016.

Rong, L. *et al.* (2016) ‘Summary of best guidelines and validation of CFD modeling in livestock buildings to ensure prediction quality’, *Computers and Electronics in Agriculture*, 121, pp. 180–

190. Available at: https://doi.org/10.1016/j.compag.2015.12.005.

Saha, C.K. *et al.* (2020a) 'Opening Size Effects on Airflow Pattern and Airflow Rate of a Naturally Ventilated Dairy Building—A CFD Study', *Applied sciences*, 10, pp. 1–17. Available at: https://doi.org/10.3390/app10176054.

Saha, C.K. *et al.* (2020b) 'Opening Size Effects on Airflow Pattern and Airflow Rate of a Naturally Ventilated Dairy Building—A CFD Study', *Applied Sciences*, 10(17), p. 6054. Available at: https://doi.org/10.3390/app10176054.

Teitel, M. and Wenger, E. (2014) 'Air exchange and ventilation efficiencies of a monospan greenhouse with one inflow and one outflow through longitudinal side openings', *Biosystems Engineering* [Preprint]. Available at: https://doi.org/10.1016/j.biosystemseng.2013.11.001.

Tomasello, N., Valenti, F. and Cascone, G. (2019) 'Development of a CFD Model to Simulate Natural Ventilation in a Semi-Open Free-Stall Barn for Dairy Cows', *Buildings*, 9(8), p. 183. Available at: https://doi.org/http://dx.doi.org/10.3390/buildings9080183.

Tominaga, Y. *et al.* (2008) 'AIJ guidelines for practical applications of CFD to pedestrian wind environment around buildings', *Journal of Wind Engineering and Industrial Aerodynamics*, 96(10), pp. 1749–1761. Available at: https://doi.org/https://doi.org/10.1016/j.jweia.2008.02.058.

Tresoldi, G., Schütz, K.E. and Tucker, C.B. (2019) 'Cooling cows with sprinklers: Effects of soaker flow rate and timing on behavioral and physiological responses to heat load and production', *Journal of Dairy Science*, 102(1), pp. 528–538. Available at: https://doi.org/10.3168/JDS.2018-14962.

Tu, J., Yeoh, G.H. and Liu, C. (2012) *Computational fluid dynamics: a practical approach*. Butterworth-Heinemann.

Vitali, M. *et al.* (2021) 'Behavior and Welfare of Undocked Heavy Pigs Raised in Buildings with Different Ventilation Systems', *Animals*, 11(8), p. 2338. Available at: https://doi.org/10.3390/ani11082338.

Wang, K., Pan, Q. and Li, K. (2017) 'COMPUTATIONAL FLUID DYNAMICS SIMULATION OF THE HYGROTHERMAL CONDITIONS IN A WEANER HOUSE IN EASTERN CHINA', 60(2014), pp. 195–205. Available at: https://doi.org/10.13031/trans.11655.

Wang, X. *et al.* (2021) 'Numerical evaluation on ventilation rates of a novel multi-floor pig building using computational fluid dynamics', *Computers and Electronics in Agriculture*, 182, p. 106050. Available at: https://doi.org/10.1016/j.compag.2021.106050.

Wang, X., Zhang, G. and Choi, C.Y. (2018a) 'Effect of airflow speed and direction on convective heat transfer of standing and reclining cows', *Biosystems Engineering*, 167, pp. 87–98. Available at: https://doi.org/10.1016/j.biosystemseng.2017.12.011.

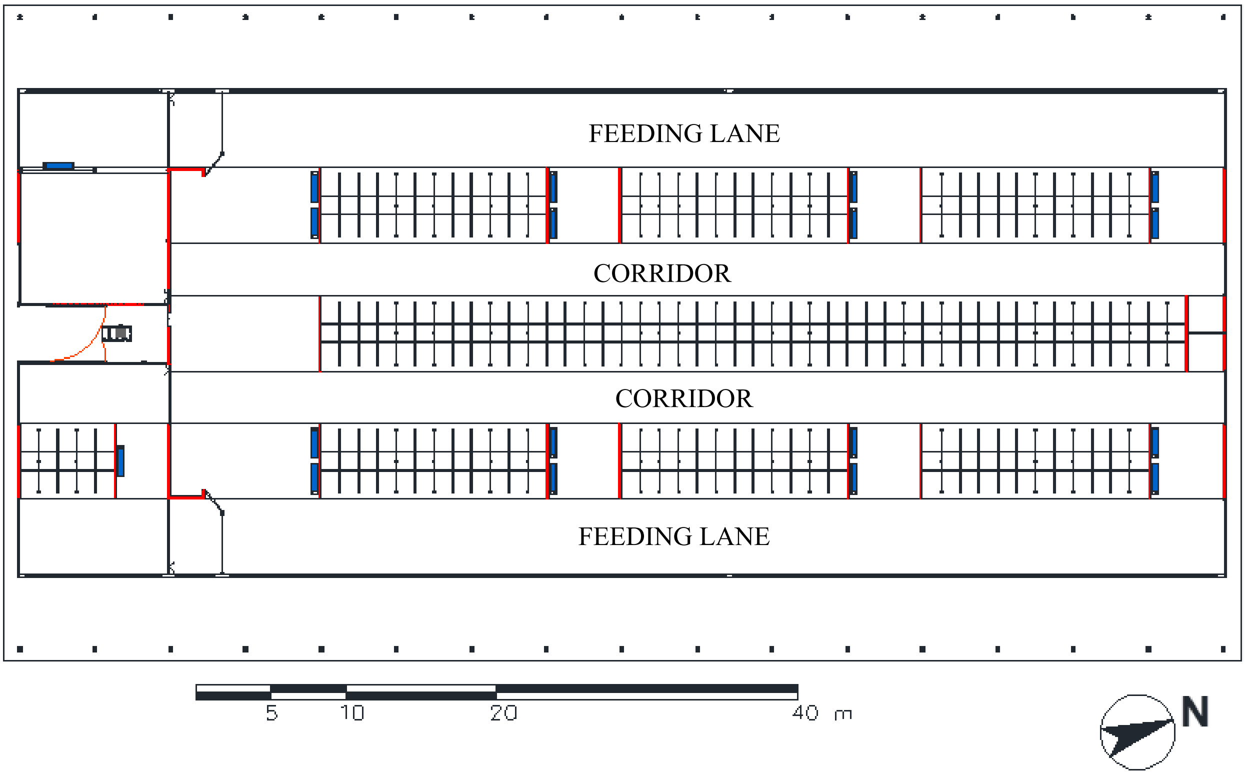
Wang, X., Zhang, G. and Choi, C.Y. (2018b) 'Evaluation of a precision air-supply system in naturally ventilated freestall dairy barns', *Biosystems Engineering*, 175, pp. 1–15. Available at: https://doi.org/10.1016/j.biosystemseng.2018.08.005.

Wu, W. *et al.* (2012) 'Evaluation of methods for determining air exchange rate in a naturally ventilated dairy cattle building with large openings using computational fluid dynamics (CFD)', *Atmospheric Environment*, 63, pp. 179–188. Available at: https://doi.org/10.1016/j.atmosenv.2012.09.042.

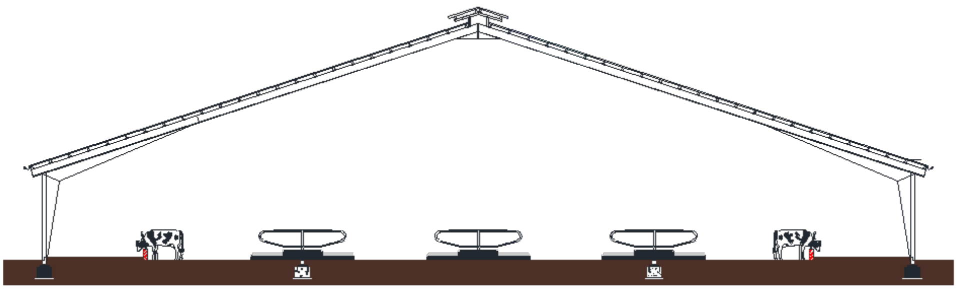
Xin, Y. *et al.* (2022) 'CFD study on the impacts of geometric models of lying pigs on resistance coefficients for porous media modelling of the animal occupied zone', *Biosystems Engineering*, 222, pp. 93–105. Available at: https://doi.org/10.1016/j.biosystemseng.2022.07.015.

Yee, H.C. (1987) 'Construction of explicit and implicit symmetric TVD schemes and their applications', *Journal of Computational Physics*, 68(1), pp. 151–179. Available at: https://doi.org/https://doi.org/10.1016/0021-9991(87)90049-0.

Zhao Zhang Wei Zhang, Z.J.Z. and Chen, Q.Y. (2007) 'Evaluation of Various Turbulence Models in Predicting Airflow and Turbulence in Enclosed Environments by CFD: Part 2—Comparison with Experimental Data from Literature', *HVAC&R Research*, 13(6), pp. 871–886. Available at: https://doi.org/10.1080/10789669.2007.10391460.

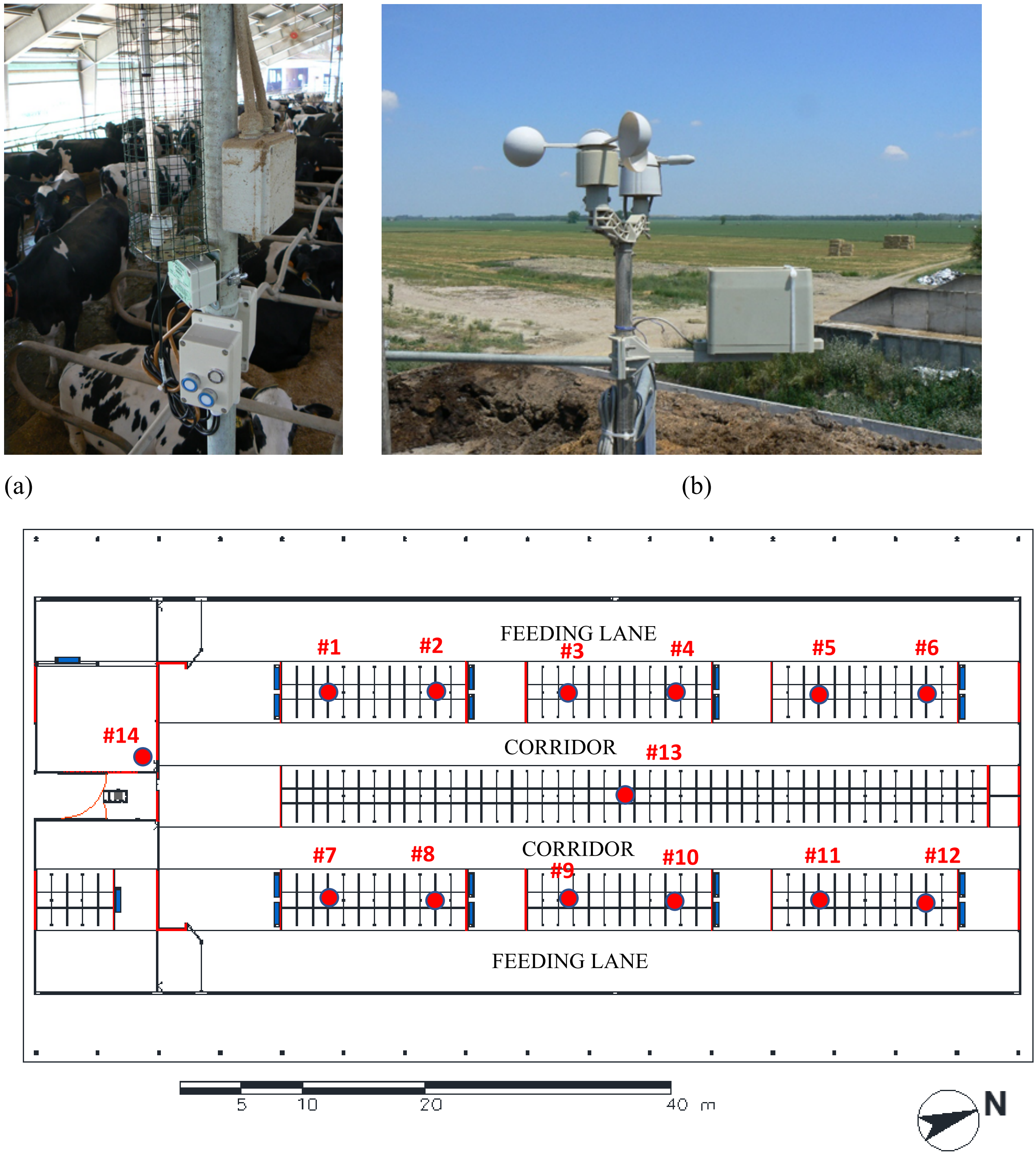


(a)



(b)

Figure 1. Views of the case study barn and its internal organization: (a) Plan view. (b) Transverse cross-section view.



(c)

Figure 2. Pictures of the Smart Monitoring System installed in the case study barn. (a) View of an indoor node positioned at a level of 2.0 m from the bedding. (b) Detail of the outdoor node located at the top of the building. (c) Position of the fourteen indoor nodes.

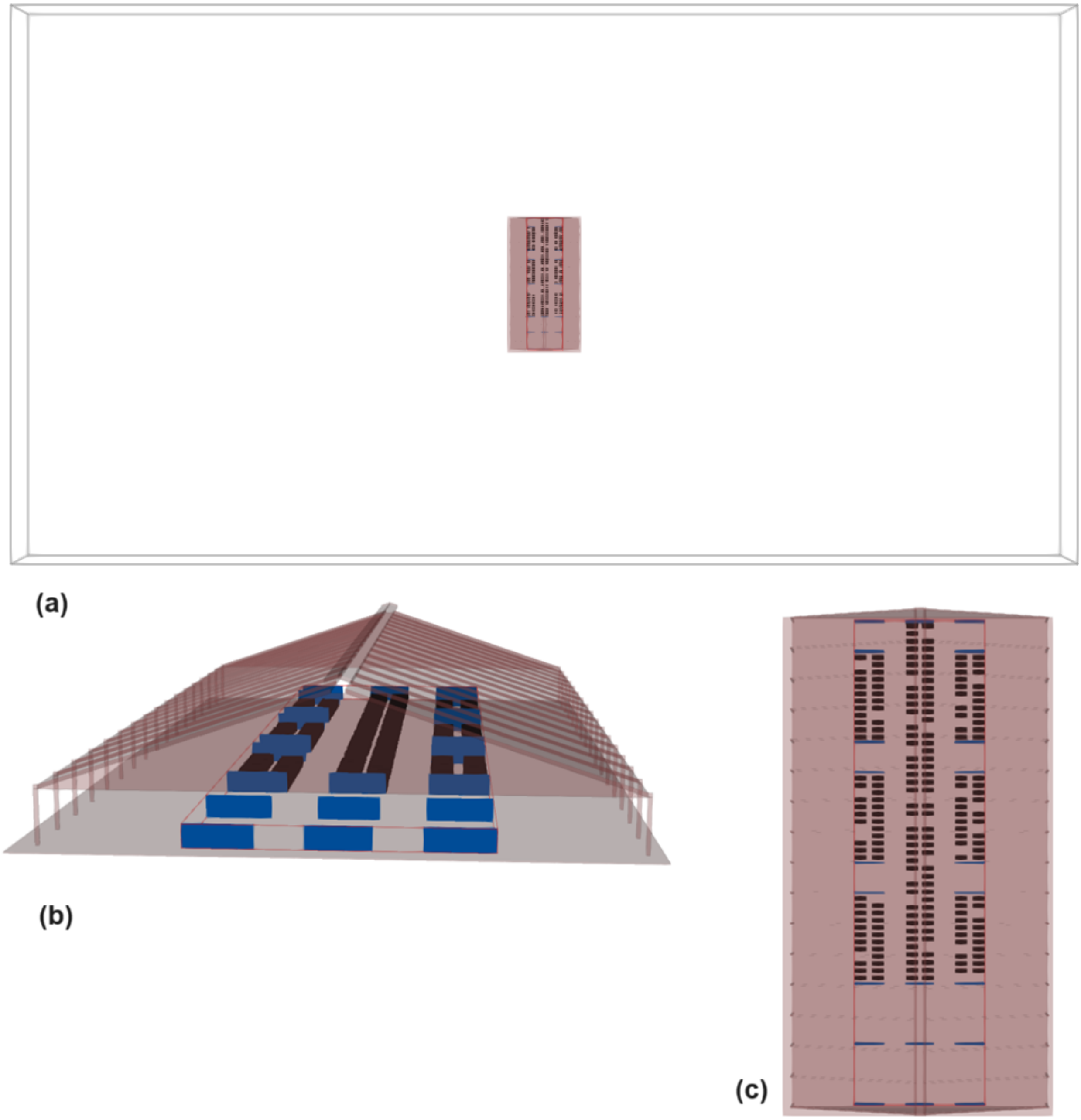


Figure 3. Views of the numerical model. (a) Global top view. (b) Lateral view with the details of the randomly placed cows. (c) Top view of the model of the barn.

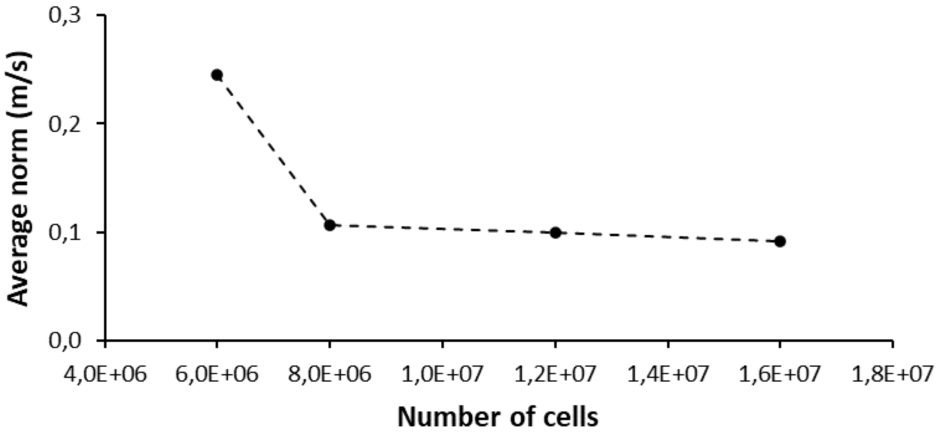


Figure 4. Trend of the average norm considered in the grid convergence study for the model with cows enabled to exchange heat.

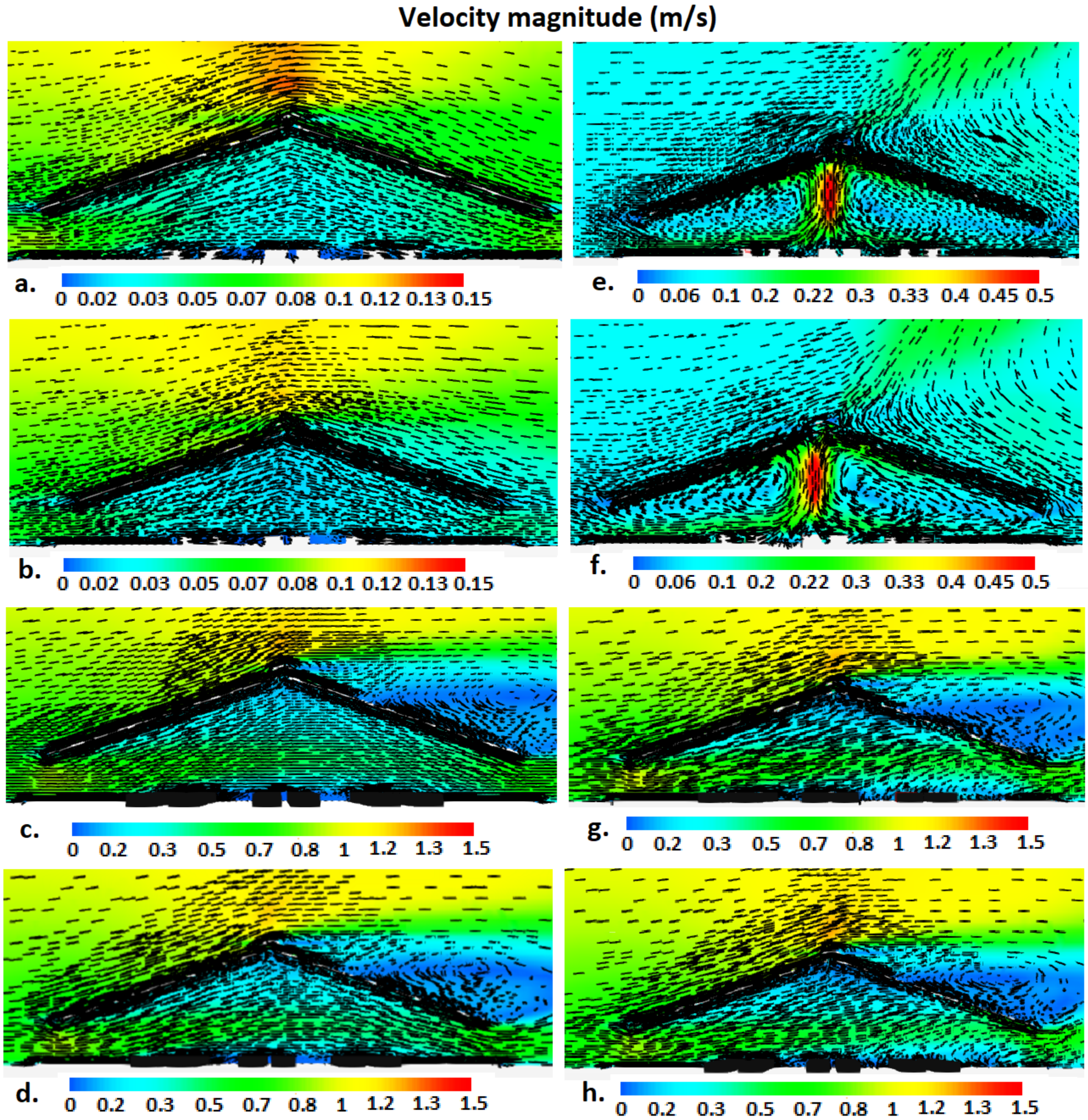


Figure 5. Contour and vector patterns of velocity magnitude (m/s) for the eight scenarios investigated: a, b, c, d show results provided by the simplified model (neglecting the animal presence in the thermal evaluation).; e, f, g, h show results provided by the enriched model, with animal able to exchange heat with the surrounding air.

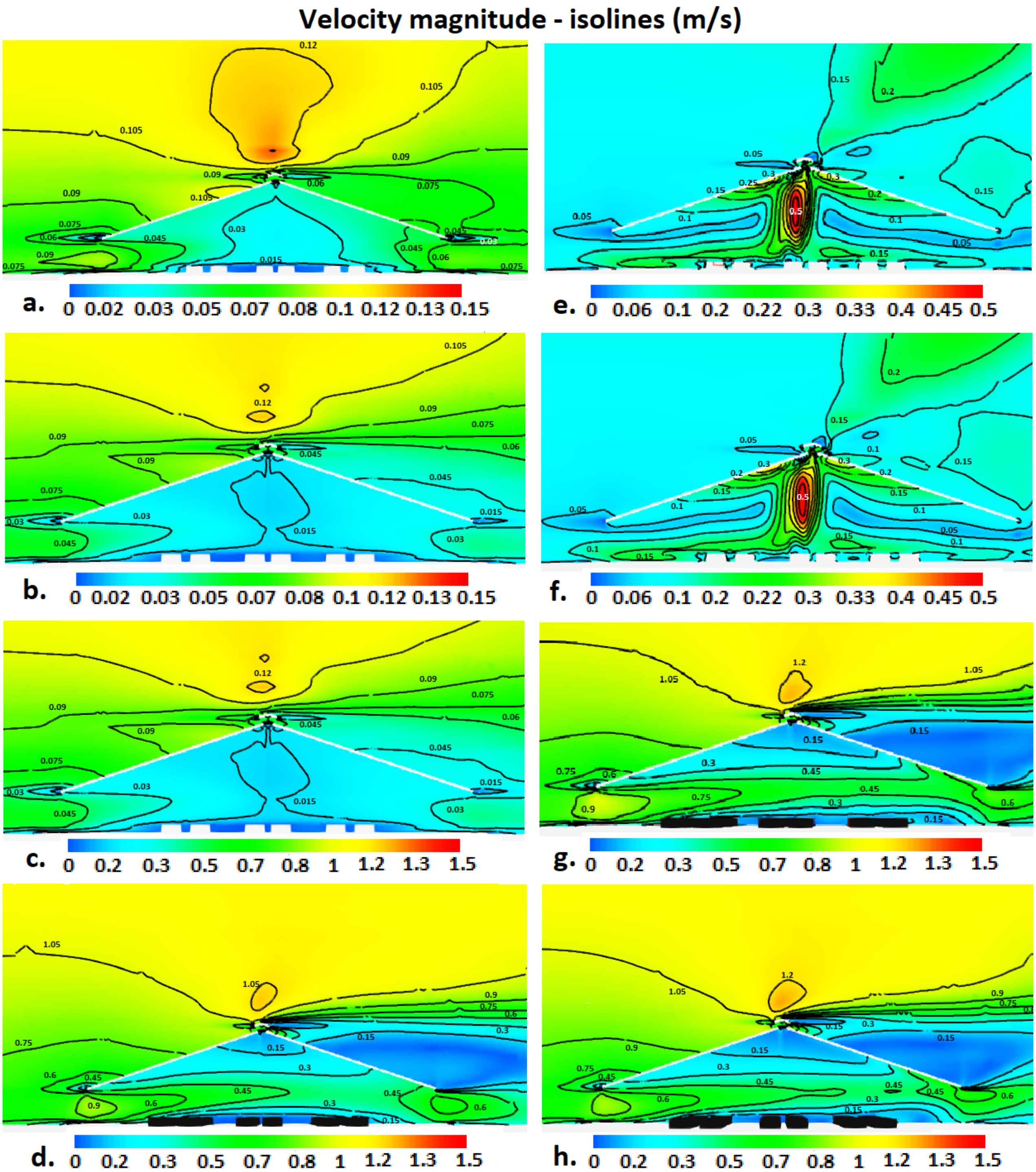
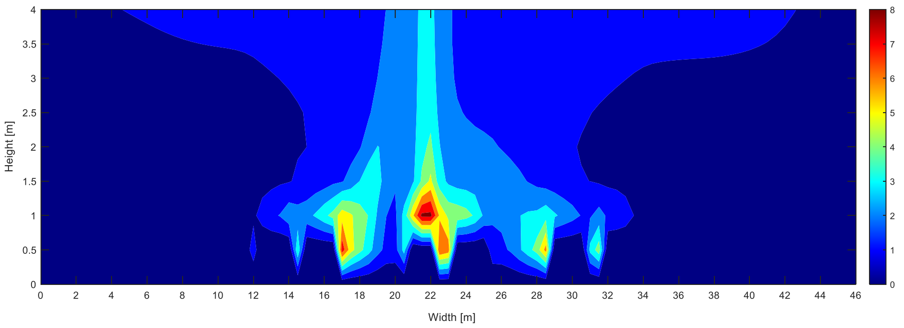
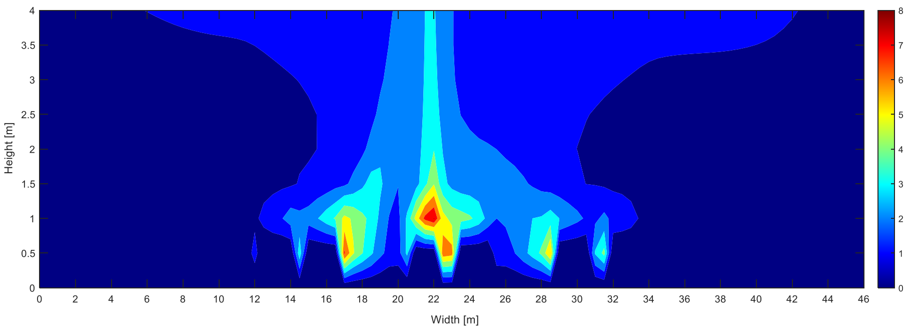


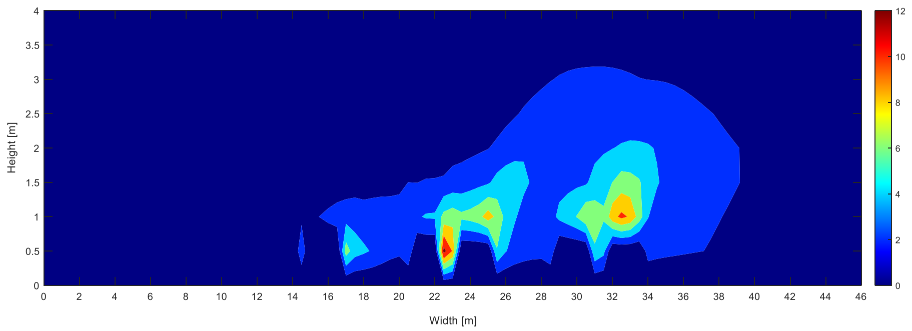
Figure 6: Contour maps with velocity isolines of velocity magnitude for the eight scenarios investigated: a, b, c, d show results provided by the simplified model (neglecting the animal presence in the thermal evaluation).; e, f, g, h show results provided by the enriched model, with animal able to exchange heat with the surrounding air.



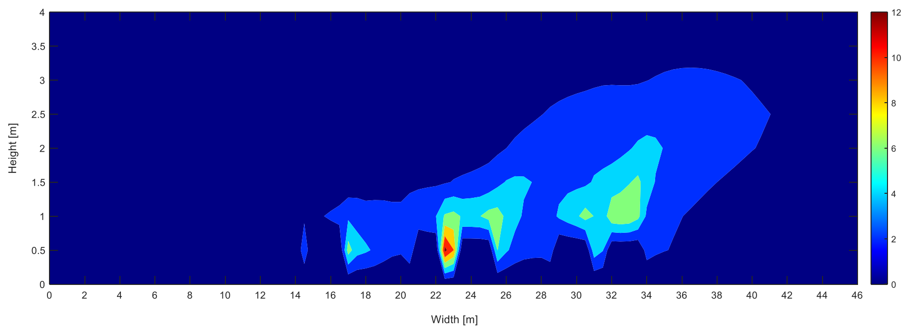
(a)



(b)



(c)



(d)

Figure 7. Contour of the temperature differences provided by enriched model and simplified model for (a) HLV, (b) CLV, (c) HHV, and (d) CHV scenarios where the scenario is based on season (C: cold or H: hot) and wind velocity magnitude (LV: low velocity or HV: high velocity).

Table 1: Boundary conditions for the considered scenarios where the scenario label is based on season (C: cold or H: hot) and wind velocity magnitude (LV: low velocity or HV: high velocity). († The reference wind velocity is referred to a level equal to 10.0 m from the ground level).

Scenario label	Outdoor temperature (°C)	Reference wind velocity† (m/s)	Wind direction (°)
HLV	24.0	0.1	270° (NW)
CLV	8.0	0.1	270° (NW)
HHV	24.0	1.0	270° (NW)
CHV	8.0	1.0	270° (NW)

Table 2. Main results of the model validation procedure where the scenario label is based on season (C: cold or H: hot) and wind velocity magnitude (LV: low velocity or HV: high velocity); MAD: Maximum Absolute Difference; RMSE: Root Mean Square Error.

Scenario label	MAD [m/s]	RMSE [m/s]	RMSE/ $\tilde{v}$ ×100 [%]
HLV	0.056	0.039	22.4 %
CLV	0.142	0.065	21.3 %
HHV	0.211	0.138	18.0 %
CHV	0.163	0.117	18.9 %