

Improving natural ventilation in renovated free-stall barns for dairy cows: Optimized building solutions by using a validated computational fluid dynamics model

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Abstract

Natural ventilation is the most used system to create suitable conditions, removing gases, introducing oxygen in livestock buildings. Its efficiency depends on several factors and above all on the number, the dimensions and the position of wall openings and internal layout of livestock buildings. The aim of this research was to develop optimized layout solutions for improving natural ventilation effectiveness in free-stall barns for dairy cows by using a CFD approach. A validated computational fluid dynamics (CFD) model was applied in a case study which is highly representative of building interventions for renovating the layout of free-stall barns for dairy cows located in an area of the Mediterranean basin. Firstly, dairy cow behaviour was analysed by visual examination of time-lapse video-recordings. Then, simulations were carried

out by using the validated CFD model and changing the position of internal and external building elements (*i.e.*, internal office and external buildings for milking) in order to find the best condition for the thermal comfort of the animals. The results showed that the best conditions were recorded for a new configuration of the building in terms of air velocity distribution within the resting area, the service alley and the feeding alley for dairy cows, and in the pens for calves. In this new layout, the office areas and the north-west wall openings were located by mirroring them along the transversal axis of the barn. Therefore, the CFD approach proposed in this study could be used during the design phase, as a decision support system aimed at improving the natural ventilation within the barn.

Introduction

Natural ventilation is the process of providing air to and removing air from an indoor space without using mechanical systems. It depends on different factors, such as the number, the type, the dimensions and the position of the wall openings as well as the building internal layout. Natural ventilation relies on both wind pressure from the surrounding environment and buoyancy forces that develop due to temperature gradients within the building (Etheridge, 2015).

Natural ventilation represents one of the most used strategies to create suitable microclimate conditions, removing gases, and introducing oxygen in livestock buildings and is generally preferred in dairy barns (Shen *et al.*, 2013) to increase air quality (Chen *et al.*, 2012; Guo *et al.*, 2015b) as well as to maintain low energy costs for the indoor climate control (Bournet and Boulard, 2010; Bjerg *et al.*, 2013).

Among several software tools suitable to study natural ventilation, those frequently used inside buildings and in the urban environment are based on computational fluid dynamic (CFD), since they offer a scientific and accurate approach (Norton *et al.*, 2007). By means of CFD-based software tools, fluid characteristics (*i.e.*, temperatures, velocities, particle concentrations, pressure and pressure coefficients) can be calculated by solving the governing Navier-Stokes equations (*i.e.*, mass, momentum and energy conservation equations) to describe the fluid dynamic properties governing airflow movement in the space and time domain (Anderson, 1995). In literature, many research studies were focused on the use of CFD-based model to improve animal well-being conditions (Vilela *et al.*, 2019). A study carried out by Gaspari *et al.* (2017) was focused on the use of CFD-based model in order to refine, re-arrange and create the most appropriate architectural shape of buildings in order to improve natural ventilation by comparing different wall-openings layouts. In selected case

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studies, Guo *et al.* (2015a, 2015b) used PHOENICS software tool in order to optimize natural ventilation by varying three different building features (*i.e.*, building site plan, building shape and the envelope). The ventilation airflow pattern in a two-bedded hospital room was analysed through CFD simulations by Méndez *et al.* (2008) to find the optimum in terms of patients comfort and building costs. Song *et al.* (2015) studied the ventilation airflow performance of a school classroom by simulating four different ventilation systems using Fluent® software tool.

Recently, in a research study (Tomasello *et al.*, 2019), a method to build a CFD model for simulating wind-driven natural ventilation in a free-stall barn for dairy cows was defined. The selected case study focused on the analysis of natural ventilation through large wall openings and was significant for the recurrence of the same type of building in an area of the Mediterranean basin (Sicily) characterised by hot climate, especially during the summer season. In the research study, the barn functional units which were more relevant for animal housing were investigated by using Ansys Fluent 17.1®. It was shown that the air velocity values inside the barn, both simulated and measured, were too low and caused discomfort to cows during hot climate.

Since the layout of free-stall barns as well as plants and equipment are often unsuitable to satisfy animal and operator requirements, the breeding environment could prove inadequate especially with regard to location and dimensions of the functional areas of the barn in relation to the microclimatic conditions. In this case, building renovations should be run in order to improve animal thermal comfort and, consequently, animal well-being, which is of utmost importance for the quality and the quantity of animal products and for farm economy and human health preservation. Several research works in literature studied the effect of microclimatic conditions on cow welfare. Heat stress induced by adverse hot climate conditions could cause feed intake reduction, decreased milk production, alteration of fertility and behavioural changes (Kadzere *et al.*, 2002; Porto *et al.*, 2017; D'Emilio *et al.*, 2017). In this regard, as reported by D'Emilio *et al.* (2017), heat stress affects the productivity of cows in a different way in relation to their production phase. Specifically, during the early lactation stages, cows are less able to counteract the adverse effects of heat stress and can have a decline in milk production. With regard to cow behaviour, Vanhoudt *et al.* (2015) demonstrated that eating, rumination, and lying down are strictly related to cow health, comfort and productivity and could be negatively affected by stress, disease, and discomfort. Other research works focused on the monitoring and analysis of feeding behaviour with the aim to optimise intake under different feeding management systems (Halachmi *et al.*, 1998; DeVries *et al.*, 2004; O'Driscoll *et al.*, 2009). These studies demonstrated that heat stress induced by hot microclimate conditions is one of the most relevant causes of cow discomfort. As stated by Fagundes *et al.* (2020), high air temperature values are included among the main stressors that negatively affect the performance of dairy cows, especially in temperate climates. Ruzal *et al.* (2011) reported that in a warm environment high air velocity contributes to decrease high air temperature and can mitigate heat stress. As stated by Seo *et al.* (2009), the control of microclimate parameters is required to increase the productivity of livestock farming and, in this context, many studies were carried out to investigate the efficacy of different cooling systems. Some papers studied the effects of systems equipped with sprinklers and fans for direct wetting of the animals combined with forced ventilation on both cow physiology (*e.g.*, reduction in rectal temperature, respiratory rate, dry matter intake, rumination time, lying time), lactation performance (milk quality and yield) (Avendaño-Reyes *et al.*,

2010; Berman, 2008, 2010; Avendaño-Reyes *et al.*, 2012) and cow behaviour (Porto *et al.*, 2017; D'Emilio *et al.*, 2017). However, some research works studied how to mitigate heat stress in dairy cows by using only passive systems, such as natural ventilation. In fact, some recent review papers on practices for alleviating heat stress of dairy cows cited some studies on the use of natural ventilation for mitigating heat stress (Fournel *et al.*, 2017).

The objective of the study reported in this paper falls within the research field that aims at improving cow thermal comfort in hot climate conditions by providing a methodology for barn renovation based on the use of a CFD model to study natural ventilation. The research work analysed a real-scale case study, *i.e.*, a free-stall barn located in a geographical area characterized by severe hot climate conditions, especially during the summer season. During this period farmers adopt different methods to mitigate cow heat stress, such as mechanical ventilation, often coupled with sprinkler systems. However, due to climate changes, severe hot climate conditions could occur also in other periods of the year, especially in late spring or in the early autumn, when natural ventilation is mostly the only means to mitigate cow heat stress. Therefore, in the first step of the study reported in this paper, cow discomfort due to microclimatic conditions was analysed by studying cow behaviour in a period characterised by the inactivity of mechanical ventilation and, therefore, natural ventilation was the only system to mitigate cow heat stress. Then, by taking advantage of the prevailing winds, a CFD model previously validated for the same free-stall barn was used to carry out simulations of different building layouts obtained by modifying some architectural building systems (*i.e.*, slope of the roof and external wall openings) as well as the position of some barn functional units (*i.e.*, internal office and external buildings for milking).

Materials and methods

The barn under study

The barn under study was selected among those located in a geographical area which is highly representative of dairy farms in the Mediterranean basin, *i.e.*, the municipality of Ragusa (Southern Italy).

In recent years, in the area under study, free-stall barns with a straw yard system have often been converted into cubicle system ones. Because of the relevance assumed by this case of building renovation as well as the incidence of open or semi-open buildings in the area under study (34% of free-stall barns for dairy cows), this research focused on the renovation of a semi-open free-stall barn assisted by a CFD-based decision support system to ensure an adequate natural ventilation within the barn.

The barn under study, with an average total number of 60-64 lactating animals and an average milk production per cow of about 1.27l/head, is located in Contrada Pozzilli (37.022845°N latitude, 14.534247°E longitude; Vittoria, Ragusa, Italy), at an altitude of approximately 230 a.s.l., among surrounding trees (nine trees located alongside the east façade and the others alongside the west one) and other rural buildings. The rectangular plan is 57 m long and 21 m wide. The pitch slope is 12%, with a height ranging between 5.4 m to 6.7 m. The main functional areas of the barn are the feeding area (composed of the feeding alley, the feeding passage and the manger), the resting area (composed of 64 stalls subdivided in three pens on the same row), a service alley and offices used for herd management. The sides of the barn are completely

open, except for a wall located on the south-west side, which has four doors (Figure 1A).

Data acquisition systems

Cow behaviour and indoor air velocity were studied in order to define the areas of the barn to be modified aimed at improving animal thermal comfort.

Dairy cow behaviour was analysed by visual examination at ten-minute scan sampling intervals of time-lapse images obtained from a multi-camera video-recording system composed of ten cameras located in the resting area (Figure 1B), mounted on steel beams with special brackets. The cameras, which were equipped with a HTTP interface and IR sensors for night vision, had a maximum resolution of 1280×960 pixels and the ability to capture up to 25 frames per second (fps).

In order to study cow behaviour during the more recurrent microclimatic conditions, the visual analysis focused on the areas of the barn where animals were housed, *i.e.*, the resting area, the feeding alley and the service alley, and was performed at the time intervals when the wind above the roof of the barn had the same direction of the prevailing wind measured by Acate wheatear stations, *i.e.*, N-E direction. Furthermore, data were acquired from 26 April 2016 to 2 May 2016, when the mechanical ventilation system installed within the barn was inactive. In fact, the farmer usually activates the mechanical ventilation combined with sprinkler systems from June to September. The selection of this time interval made it possible to obtain a representative data sample related to cow behaviour in the specific condition of the study, *i.e.*, under natural ventilation.

The visual analysis focused on the classification of five different cow behaviours among those most frequently considered for their high relation to cow well-being (DeVries *et al.*, 2003; Provolo and Riva, 2009; Bava *et al.*, 2012; D'Emilio *et al.*, 2018): 'lying', all the possible decubitus positions in the cubicle; 'feeding', standing positions in the feeding alley; 'standing', standing positions in the alleys; 'perching', standing with front feet in the stall and the rear feet in the alley; 'drinking', head over the drinking trough position.

The indoor sensors for monitoring the microclimatic parameters were located as depicted in Figure 1A. A measurement system based on data-logger CR10X (Campbell, UK) connected to both sensors of air temperature and relative humidity (Rotronic Italy s.r.l., Italy) and sensors for the measurement of velocity and direction of indoor air (anemometers WindSonic, Gill Instruments Ltd., UK), was used to acquire data at 5-min time intervals. Sensors were located in the resting area at 2.50 m above the floor, and outside the barn at 7.50 m above the floor. Furthermore, data from the nearby weather station located in Acate (SIAS, 2016) were acquired for the same time intervals and processed to define both the average hourly wind speed (ms^{-1}) and the average hourly wind direction ($^{\circ}$), at a 10 m reference height.

The computational fluid dynamics model validated for the barn under study

The 3D model of the free-stall barn was developed by using Autodesk Autocad 2016[®] and was imported into Ansys ICEM CFD 17.1[®] to build the mesh and assign the boundary conditions. Since the selected case study has some peculiarities, such as the position of trees and buildings located in the surroundings of the barn and a three-open side barn, the modelling process for the mesh generation was reported as follows to allow its repeatability. Firstly, the model in IGES format was imported in Ansys ICEM

17.1[®] (Ansys Inc., version 17.1, Canonsburg, PA, USA) and the geometry was repaired with a tolerance equal to 0.01 in order to verify the 'correctness' of the model, because the tolerance is related to the accuracy of the surface-to-surface proximity calculation. Then, the 'body' (*i.e.*, the fluid 'air') was defined. The next step was the domain decomposition, *i.e.*, splitting the domain into smaller blocks and then generating separate meshes for each individual block. Because of the complexity of the geometry (*i.e.*, shape of the roof and buildings located in the surroundings of the barn), this phase was particularly burdensome. In fact, many tests were carried out to obtain blocks that were as much as possible 'regular' from the point of view of side dimensions and corner angles. The blocks of the mesh regarding the modelling of the barn offices, the raised floor of the feeding passage, the buildings and the trees located in the surroundings of the barn, were isolated and were not exported to Ansys Fluent 17.1[®].

During the meshing process, the following parameters were set: the spacing at beginning and end of the edge was set to 0.1 close to solids and 0.0 in the remaining points. The expansion ratio between two consecutive cells was set to 1.3. This value, although slightly higher than that reported in literature (Bartzis *et al.*, 2004), was chosen because of the high computational costs. After defining the boundary conditions as reported by Tomasello *et al.* (2019), the generated mesh was converted into an unstructured mesh and exported to Ansys Fluent 17.1[®], set as output solver (Figure 2A and B). The mesh has about 7.95 million cells and about 8.15 million nodes. Paying attention to computational costs, the mesh was built with elements having a finer resolution close to the solids and within the building. The mesh face areas range between 2.7^{-3} m^2 and 8.7 m^2 .

Finally, the numerical simulations were carried out by using the Ansys Fluent 17.1[®] software in steady-state conditions and a standard K- ϵ turbulence model.

In a first existing barn layout the hourly average data acquired from the meteorological station nearby the barn located in Acate (SIAS, 2016) were considered as input. Then, in order to compare simulated and measured data, the hourly average data obtained from the measuring system installed within the barn and previously described were compared with those obtained by simulations.

The phases of 3D modelling, mesh generation and CFD simulations were carried out on a desktop computer (Intel(R) Core (TM) i7-7700 CPU, 3.60 GHz processor, 8.0 GB RAM). The residuals were reduced at four orders of magnitude and the convergence was not assumed to be reached until both the velocity magnitude at the monitoring points and the residual stabilized (Tomasello *et al.*, 2019). The iteration steps required to reach a convergent solution were about 1500.

By using the CFD methodology described by Tomasello *et al.* (2019), the airflow distribution was modelled. The model was validated by comparing measured and simulated data, since it was found that the airflow distribution reflected the real conditions recorded inside the barn, where both the building layout and the characteristics of the openings strongly affected air velocity.

Furthermore, after CFD simulation, the average air velocity in the areas relevant for housing dairy cows and calves were computed. These air velocity values were very low, *i.e.*, 0.42 ms^{-1} in the resting areas, service alley and feeding alley and 0.67 ms^{-1} in the pens for calves. Therefore, the analysis of other building design configurations was crucial to achieve a higher air velocity and consequently, since elevated air velocity can alleviate heat stress as stated by Ruzal *et al.* (2011), an improvement of animal well-being, as was suggested by Bailey *et al.* (2016).

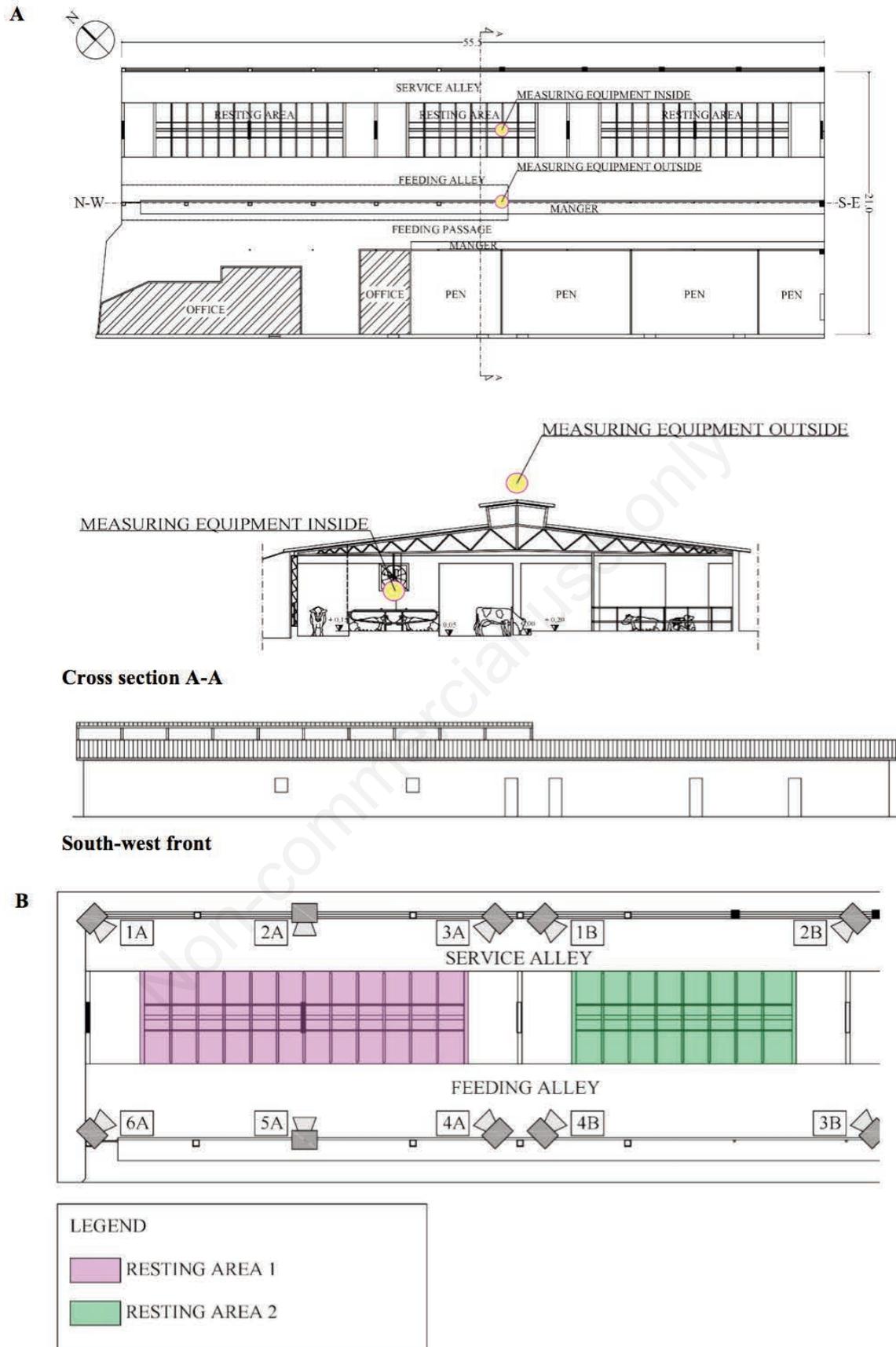


Figure 1. A) Plan of the barn. B) Video-camera system installed in the barn.

Study of air velocity distribution in different cases of building renovation

By following the methodology adopted by Tomasello *et al.* (2016) to simulate the airflow distribution in the existing barn layout, different cases of building interventions for barn renovation were modelled and simulated (Figure 3). In order to compare these different renovation solutions with the previous results, the external climate conditions, *i.e.*, average air velocity and wind direction at inlet were set equal to those used in the existing barn layout, *i.e.*, 3.85 ms^{-1} and north-east, respectively. In the simulations, only the position of the trees located in the area surrounding the barn was not changed, instead some buildings located nearby the barn were moved in other positions compared to the original ones (Figure 2C).

The cases related to the new building solutions which were modelled and simulated were:

- Case 1: the offices located within the barn and the north-western wall with openings were located by mirroring them along the longitudinal axis of the barn. With the aim of keeping the functional relationship between indoor and outdoor areas unchanged, the buildings for milking, which were located in the surrounding area of the barn, were not moved (Figure 3B);
- Case 2: the offices located within the barn and the north-western wall with openings were located by mirroring them along the transversal axis of the barn. The surrounding buildings were moved, in order to keep the functional relationship between indoor and outdoor areas unchanged;

- Case 3: each opening located in the south-west wall was doubled, thus reaching an area of about 5.5 m^2 . The buildings located in the surrounding area of the barn and the offices located within the barn were not moved;
- Case 4: the pitch slope was modified from 12% to 25%. The buildings located in the surrounding area of the barn and the offices located within the barn were not moved.

The simulations carried out for each case previously described were compared with the aim of evaluating the best solution in terms of increasing natural ventilation in the areas of the barn where cows and calves were housed. Two section plans were considered to analyse the results of the simulations, *i.e.*, section plans A and B, respectively located vertically in front of the offices and horizontally at a height of the cow snout (Figure 4).

Results and discussion

Results of the cow behaviour analysis

The results of cow behaviour analyses, which were carried out by visual observation of the areas of the barn where animals were housed, *i.e.*, the resting area, the feeding alley and the service alley, are reported in Table 1. The indoor air velocity, recorded within the considered time intervals, ranged between 0.24 ms^{-1} and 1.23 ms^{-1} with an average value of about 0.66 ms^{-1} . The outdoor air velocity values, which were recorded within the same time intervals at the

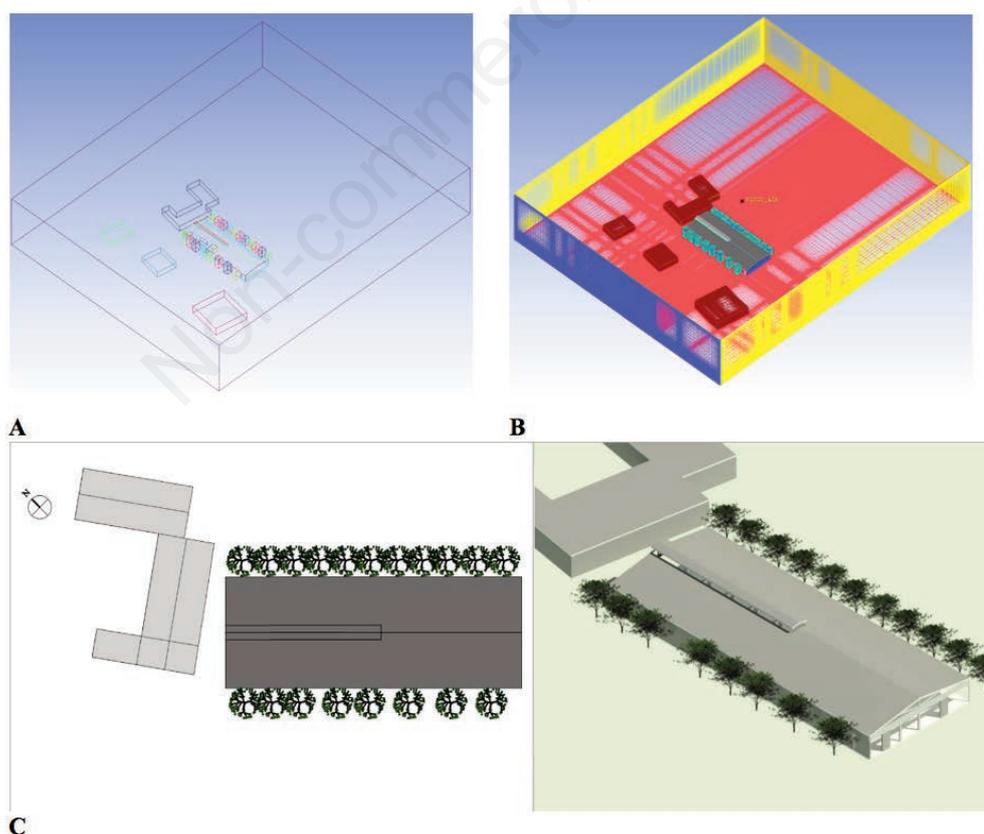


Figure 2. A) Mesh generation: The model imported in Ansys ICEM CFD 17.1®; B) Mesh generation: The final unstructured mesh; C) Barn and objects located in the surrounding areas.

Table 1. Analysis of cow behaviour within the resting area, the feeding alley and the service alley.

Simulation (mm/dd-hh)	Air velocity at weather station (10 m height) (ms ⁻¹)	Air velocity measured inside the barn (ms ⁻¹)	Cows lying in cubicles (%)	Feeding cows (%)	Standing cows (%)	Perching cows (%)	Drinking cows (%)
(04/27-10 p.m.)	1.90	0.24	24.80	34.67	22.77	13.21	4.55
(04/28-2 a.m.)	2.90	0.40	30.30	31.69	22.70	11.92	3.39
(04/28-6 a.m.)	2.70	0.44	52.18	28.24	11.57	1.76	6.26
(04/28-7 a.m.)	2.70	0.46	10.67	80.48	0.48	8.36	-
(04/28-7 p.m.)	6.40	0.98	36.15	54.34	3.79	2.21	3.51
(04/28-8 p.m.)	6.00	0.79	73.74	15.65	4.55	5.58	0.48
(04/28-9 p.m.)	7.80	0.89	79.30	9.60	5.55	2.52	3.03
(04/28-10 p.m.)	7.90	1.07	65.15	22.42	7.07	4.14	1.21
(04/29-12 p.m.)	5.80	0.95	67.68	18.28	4.04	7.88	2.12
(04/29-1 a.m.)	6.80	1.10	61.11	26.77	0.51	7.07	4.54
(04/29-2 a.m.)	8.20	1.23	67.24	18.94	5.33	6.69	1.79
(04/29-3 a.m.)	6.80	1.02	74.24	5.56	9.40	9.29	1.52
(04/29-5 a.m.)	8.50	0.89	54.55	18.18	9.09	18.18	-
(04/30-12 p.m.)	2.00	0.32	50.17	32.49	6.24	7.38	3.71
(04/30-1 a.m.)	2.50	0.27	41.92	43.93	7.08	5.04	2.02
(04/30-2 a.m.)	2.00	0.32	45.95	41.42	6.56	5.05	1.01
(05/01-1 a.m.)	2.80	0.45	66.16	18.68	10.10	5.06	-
(05/01-2 a.m.)	2.00	0.39	50.33	32.66	10.94	6.06	0.00
(05/01-5 a.m.)	1.40	0.32	30.30	54.55	6.06	9.09	0.00

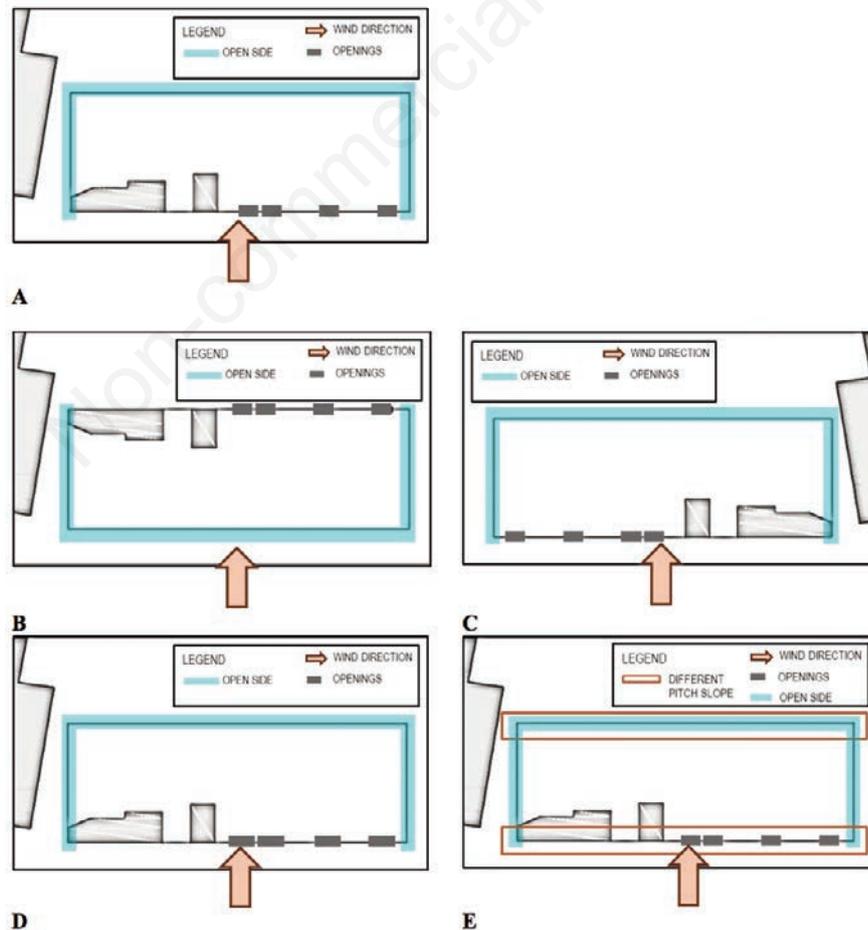


Figure 3. Alternative building design configurations: A) Existing barn layout; B) Case 1; C) Case 2; D) Case 3; E) Case 4.

weather station, ranged between 1.40 ms^{-1} and 8.50 ms^{-1} with an average value of about 4.58 ms^{-1} . Minimum and maximum values recorded for both indoor and outdoor air velocity did not occur within the same time intervals, therefore, there is not a correlation between indoor and outdoor air velocities (Table 1).

By grouping air velocity values recorded inside the barn in three different air velocity ranges, it is possible to observe a higher percentage of lying behaviour, and a decrease of standing and feeding, when air velocity intensity increased (Figure 5A). Perching and drinking behaviours were almost uninfluenced by air velocity. As shown in Figure 5A the high values of air velocity are recorded mainly during the night, when the cows usually are in the cubicles. It is well known that data could be influenced by milking, but in the selected case study milking intervals are at 5:00-6:00 a.m. and 5:30-6:30 pm, therefore outside the selected time intervals.

Therefore, Figure 5B shows the percentages for each analysed cow behaviour, considering an average indoor air velocity of 0.66 ms^{-1} , recorded within the considered time intervals.

These results were used to evaluate a potential correlation between the air velocity measured inside the barn and the cow behaviour within the resting area, the feeding alley and the service alley, and helped to check cow heat stress, since, as reported by Ruzal *et al.* (2011), high air velocity can alleviate heat stress in a warm environment.

Results of air velocity distribution within the alternative building design configurations

The results of the simulations, which were carried out by taking into account the cases of the new building layout solutions reported in Figure 3, showed in section plans A and B, are discussed below.

In Case 1, section plan A shows that the air velocity increases with height. However, due to the displacement of the wall from south-west to north-east, air velocity decreases close to the north-east side of the barn. In particular, the airflow partially goes out through the chimney, while the remaining part is hampered by the pitch of the roof. Figure 6A and B show an airflow vortex nearby the floor due to the crossing of the airflows coming from the barn openings in the south-east and north-west sides, and an airflow vortex in the upwind region.

With regard to section plan B, due to the airflow coming from the three open sides, vortices are located in the central part of the barn. In particular, it can be observed that the airflow coming from south-west goes to north-west and south-east to reach the two open sides of the barn by avoiding the wall. Air velocity peaks are higher at the three open sides, while the lowest air velocity values are detected close to the offices and between them. The airflow from the south-west side is the highest due to the absence of the windward wall (Figure 6C and D).

In Case 2, as well as in Case 1, section plan A shows that the outdoor air velocity increases with height. Highest values of air velocity were recorded when air velocity had overtaken the barn roof (Figure 7A and B).

As regards section plan B, the airflow vortices are located in the north-west, in the south-east and in the central part of the barn, due to the airflows coming from the three open sides. The vortex located in the south-east part of the barn has an air velocity higher than the one recorded for the vortex located in the north-west part of the barn, due to the different entering velocities of the air, in synergy with the wake of the downstream flow of the building. Highest air velocity peaks occur at the two extremes of north-east opened side and the south-west openings, while the lowest air

velocity values are detected, like in Case 1, close to the offices and between them (Figure 7C and D).

The results of the simulations carried out for Case 3 show that air velocity increases in the central part of the barn, where the airflows coming from the south-west wall openings and the north-

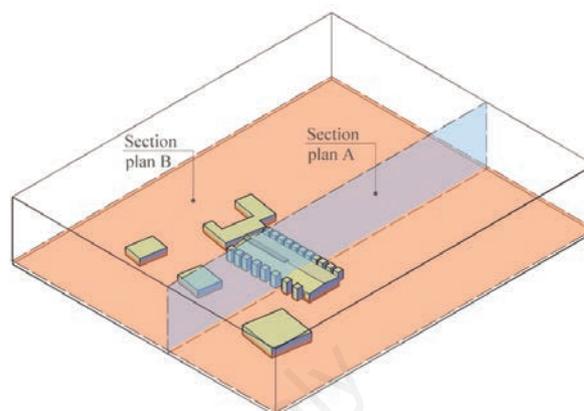


Figure 4. Identification of the considered section plans.

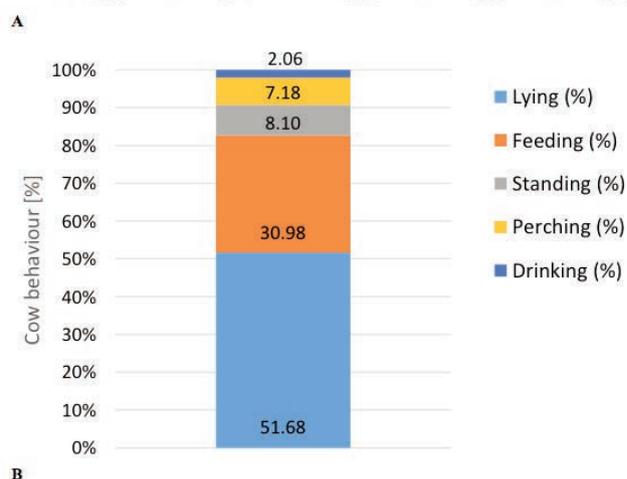
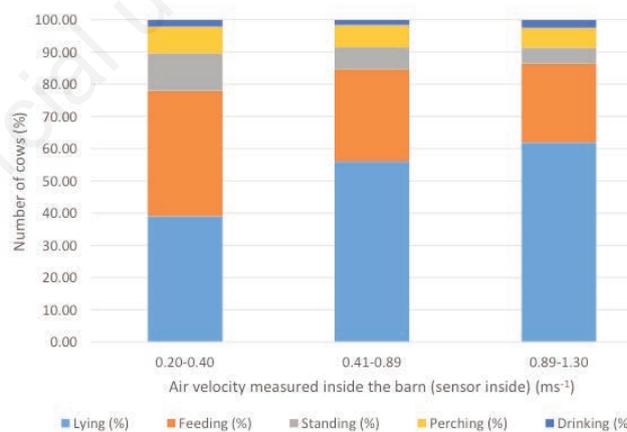


Figure 5. A) Analysis of cow behaviour within the resting area, the feeding alley and the service alley. B) Percentages of the different cow behaviours at an average air velocity of 0.66 ms^{-1} measured by the indoor sensor.

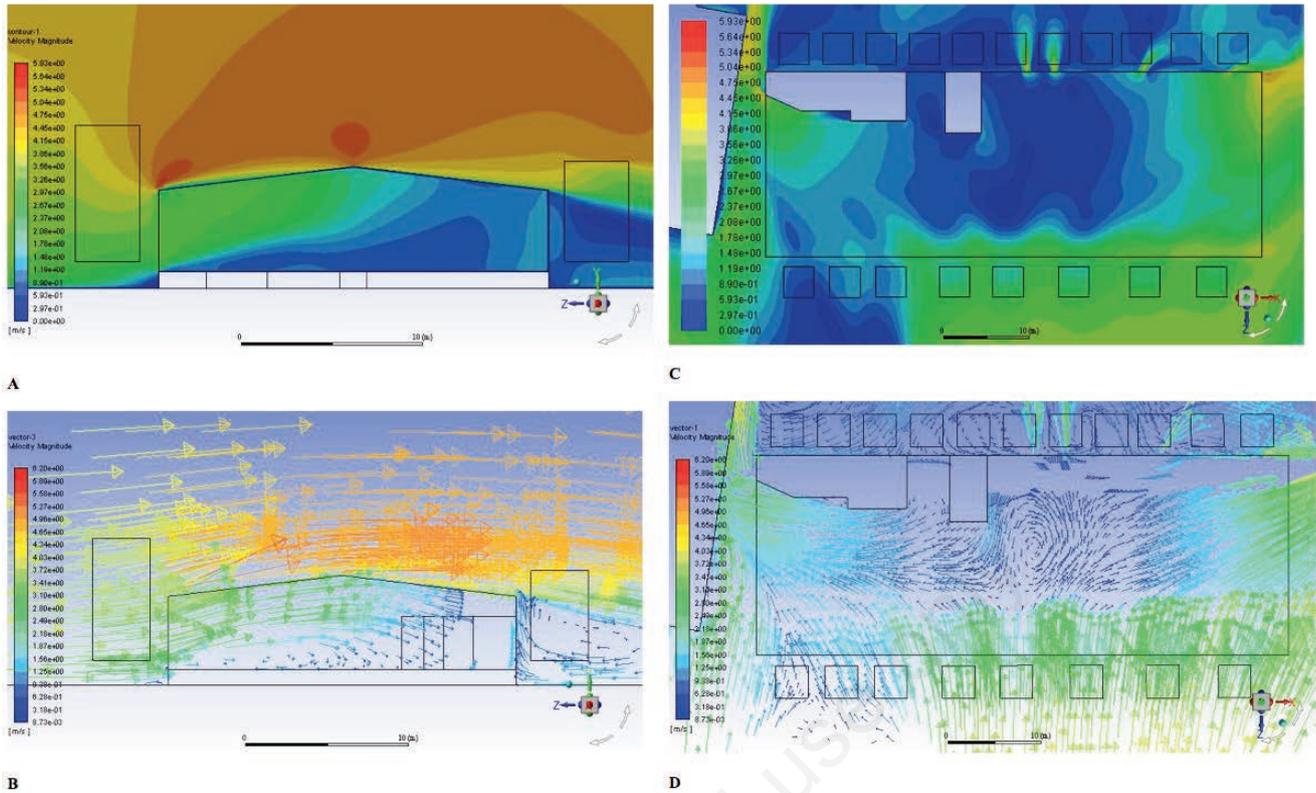


Figure 6. Case 1. A) Section plan A - air velocity distribution (ms^{-1}); B) Section plan A - distribution of air velocity vectors (ms^{-1}); C) Section plan B - air velocity distribution (ms^{-1}); D) Section plan B - distribution of air velocity vectors (ms^{-1}).

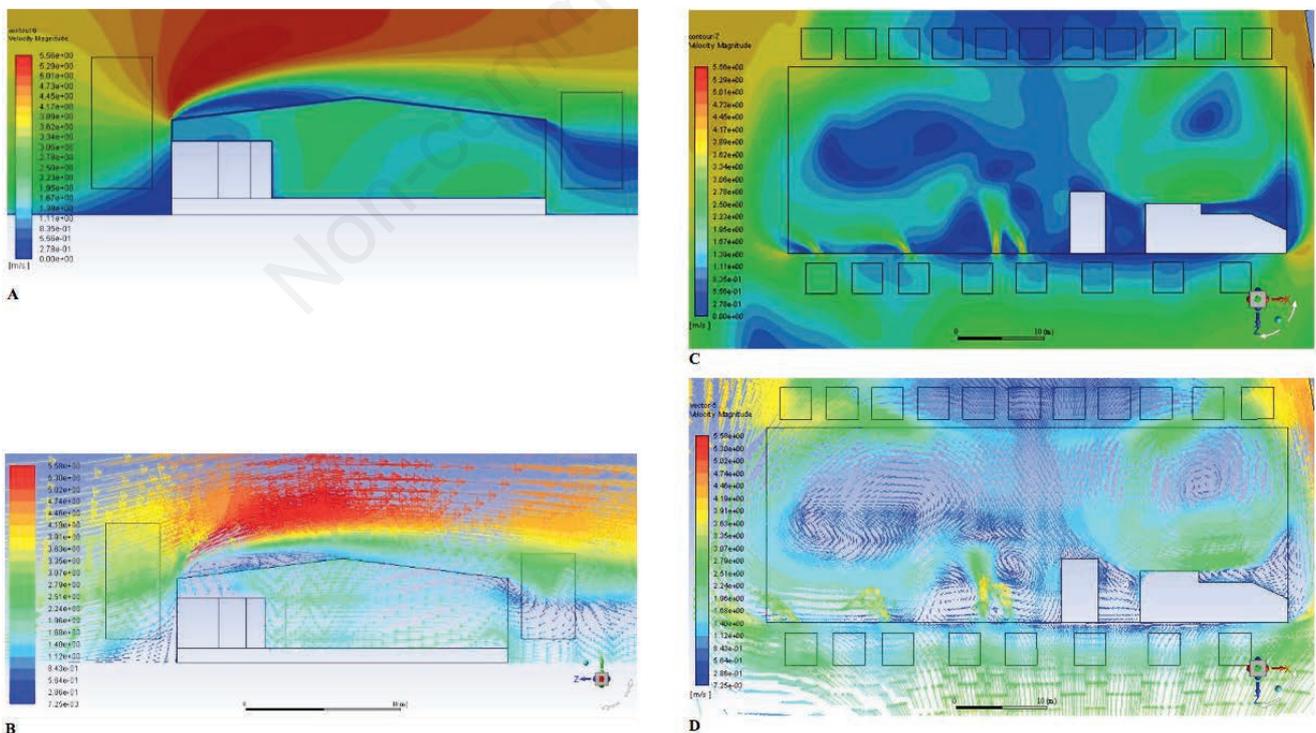


Figure 7. Case 2. A) Section plan A - air velocity distribution (ms^{-1}); B) Section plan A - distribution of air velocity (ms^{-1}); C) Section plan B - air velocity distribution (ms^{-1}); D) Section plan B - distribution of air velocity vectors (ms^{-1}).

east and south-east sides cross the barn and generate a vortex. Then, if we take into account the north-east direction, air velocity decreases, especially close to the barn roof. As shown in Case 2, the outdoor air velocity increases with the height by reaching its highest value after it overtakes the barn roof (Figure 8A and B).

If we consider section plan B, the above-mentioned vortex can be observed in the east part of the barn. Another vortex is located in the north part of the barn, due to the intersection of airflows coming from north-west and north-east. As expected, air velocity peaks are higher at the south-west openings, while the lowest air velocity values are detected close to the offices, between them and between the openings (Figure 8C and D). As to the surrounding buildings and trees, they influence slightly the airflow, which is firstly slowed down by the south-west building and then diverts close to the south-west wall, by increasing, consequently, air velocity after overtakes these obstacles.

In Case 4, as shown in section plan A (Figure 9A and B), the air velocity inside the barn is lower than the one recorded outside, due to the south-west wall, since it has an obstructive effect. The

outside airflow increases its velocity only after overtaking the barn. In the leeward area, due to the open north-east side that causes air recirculation, a wake of the airflow over the building can be detected (Figure 9A).

As shown in section plan B, the vortices are located in the northern and eastern parts of the barn, because of the airflow coming from the three open sides. The highest air velocity peaks were recorded at the two extremes of north-east opened side and at the openings located on the south-west wall, while the lowest air velocity values are detected close to the offices and between them. Also, in this alternative, the airflow decreases close to the obstacles and increases after overtaking them. Furthermore, the airflow decreases its velocity and diverts near the south-west wall (Figure 9C and D).

As reported in the introduction, a comparison was carried out between the air velocity results within the resting area, the service alley and feeding alley for dairy cows and in the pens for calves, in order to find the optimal building layout, *i.e.*, with the highest value of air velocity (Table 2).

Table 2. Comparison between air velocity results in the considered areas.

Building design configuration	Average air velocity in the resting area and alleys for dairy cows (ms^{-1})	Average air velocity in the pens for calves (ms^{-1})
Existing barn layout	0.42	0.67
Case 1	1.27	1.25
Case 2	1.38	1.42
Case 3	1.18	1.29
Case 4	1.26	1.20

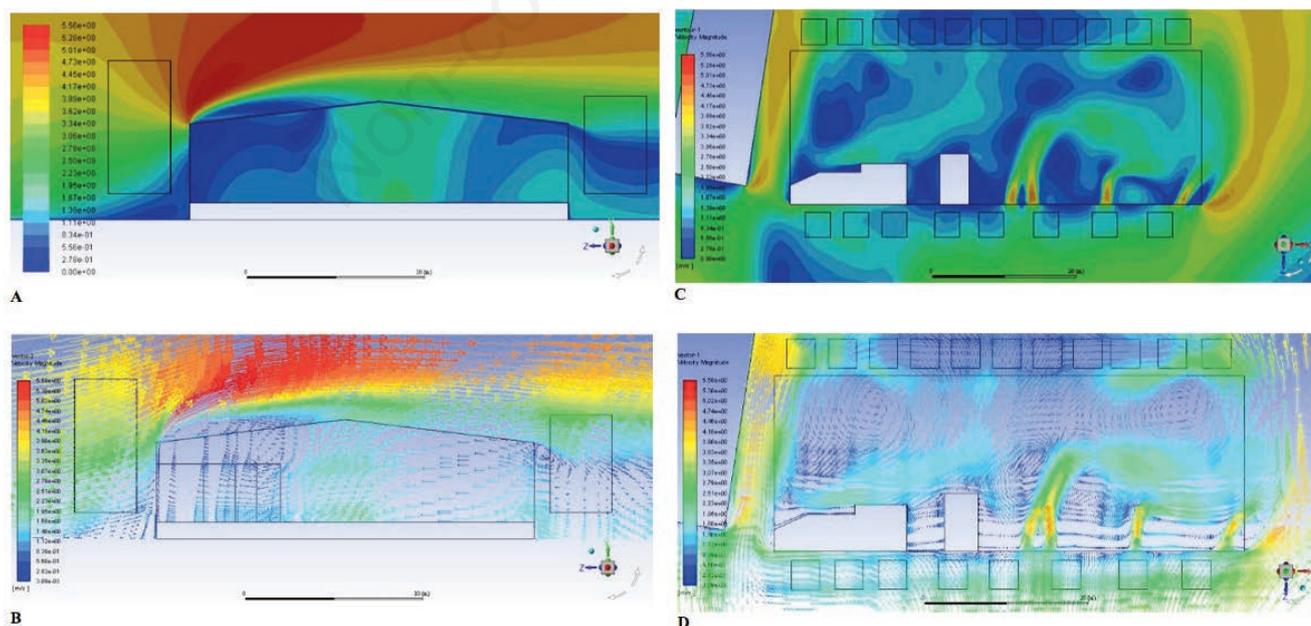


Figure 8. Case 3. A) Section plan A - air velocity distribution (ms^{-1}); B) Section plan A - distribution of air velocity vectors (ms^{-1}); C) Section plan B - distribution of air velocity (ms^{-1}); D) Section plan B - distribution of air velocity vectors (ms^{-1}).

Discussion

Data related to the cow behaviour within resting area showed that, when air velocity ranged between 0.24 ms^{-1} and 1.23 ms^{-1} , the percentage of lying cows highly increased. This growth corresponds to a discomfort reduction, as reported by Cook *et al.* (2007) and Allen *et al.* (2015) who highlighted a possible correlation between standing time per day during hot periods, lost production and disease prevalence. In particular, air velocity changes influence the convection cooling of cattle, thus causing a significant impact on the regulation of cow thermal balance (Davis and Mader, 2003), as clearly demonstrated by the correlation between air velocity and almost all the considered indices used for the heat stress assessment (Bjerg *et al.*, 2016). Specifically, as reported by Bailey *et al.* (2016), the air velocity suggested to avoid dairy cattle heat stress ranges from 1.8 to 2.8 ms^{-1} . Therefore, other building layout configurations aimed at optimizing air velocity were analysed in order to improve cow well-being. The analysis of the results of the CFD simulations carried out in this study revealed that, over the selected monitoring period, Case 2 is the building layout that makes it possible to increase the air velocity detected in the existing barn layout with a value that is closer to the one hypothesized by Bailey *et al.* (2016). In fact, average air velocity increased from 0.42 ms^{-1} to 1.38 ms^{-1} (Table 2) within the resting areas, service alley and feeding alley. Similarly, the average air velocity increased from 0.67 ms^{-1} to 1.42 ms^{-1} (Table 2) within the pens for calves, but this increment could cause health problems (enteric, respiratory).

Conclusions

In this research study, a CFD methodology was used to find the most suitable building layout for the barn in order to improve natural ventilation by increasing air velocity in the areas which were considered more relevant for animal well-being.

Firstly, a potential discomfort in cows was observed by analysing dairy cow behaviour in the selected time intervals through the visual examination of time-lapse video-recordings. In particular, it was possible to notice that in some seasons (*i.e.*, spring or summer) and under hot climate conditions, the required ventilation needed for animal well-being was not ensured. During the design phase, a better ventilation could have been obtained by the exploitation of prevailing winds coming from the north-east side.

Then, the CFD methodology was applied by taking into account five different building layouts. In Case 1, the office area and the north-western wall with openings were located by mirroring them along the longitudinal axis of the barn. In Case 2, the office area and the openings of north-western wall were located by mirroring them along the transversal axis of the barn. The buildings for milking have been moved, in order to keep the relationship between indoor and outdoor areas and activities unchanged. In Case 3, each opening of north-western wall was doubled, by covering an area of about 5.5 m^2 . In Case 4, the pitch slope was changed from 12% to 25%. By comparing the air velocity results within the resting area, the service alley and feeding alley for dairy cows and in the pens for calves, Case 2 proved to have the optimal building layout for increasing air velocity.

Future implementations of this research by improving the adopted measurement model could focus on the analysis of the nat-

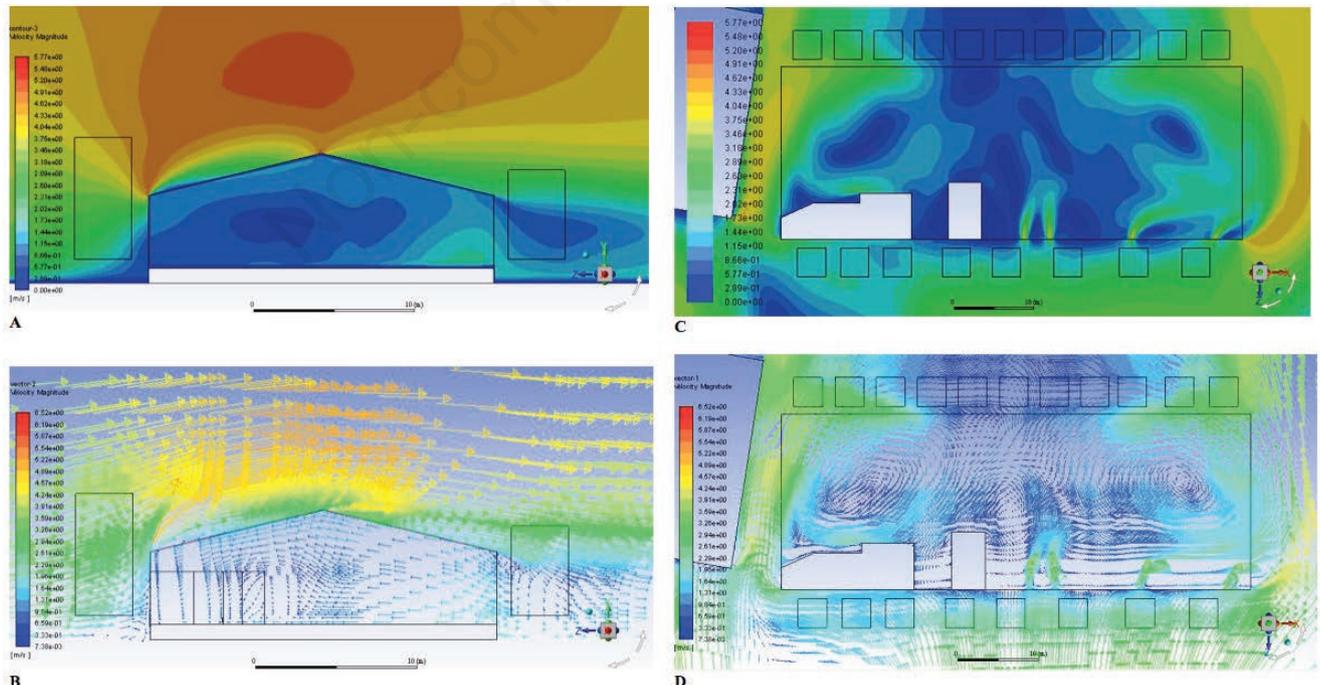


Figure 9. Case 4. A) Section plan A - air velocity distribution (ms^{-1}); B) Section plan A - distribution of air velocity vectors (ms^{-1}); C) Section plan B - air velocity distribution (ms^{-1}); D) Section plan B - distribution of air velocity vectors (ms^{-1}).

ural ventilation within the barn by taking into account both the other wind directions and different seasons of the year. Further research works could study the relationship between the temperature humidity index (THI), air velocity values and dairy cow behaviour. Alternative building renovation hypotheses - which take into consideration interventions such as the change of the resting area surface - could also be analysed.

References

- Allen J.D., Hall L.W., Collier R.J., Smith J.F. 2015. Effect of core body temperature, time of day, and climate conditions on behavioral patterns of lactating dairy cows experiencing mild to moderate heat stress. *J. Dairy Sci.* 98:118-127.
- Anderson J.D. 1995. *Computational fluid dynamics*. Springer, Berlin, Germany.
- Avendaño-Reyes L., Álvarez-Valenzuela F.D., Correa-Calderón A., Algáandar-Sandoval A., Rodríguez-González E., Pérez-Velázquez R., Macías-Cruz U., Díaz-Molina R., Robinson P.H., Fadel J.C. 2010. Comparison of three cooling management systems to reduce heat stress in lactating Holstein cows during hot and dry ambient conditions. *Livestock Sci.* 132:48-52.
- Avendaño-Reyes L., Hernández-Rivera J.A., Álvarez-Valenzuela F.D., Macías-Cruz U., Díaz-Molina R., Correa-Calderón A., Robinson P.H., Fadel J.G. 2012. Physiological and productive responses of multiparous lactating Holstein cows exposed to short-term cooling during severe summer conditions in an arid region of Mexico. *Int. J. Biometeorol.* 56:993-9.
- Bailey T., Sheets J., McClary D., Smith S., Bridges A. 2016. Heat abatement. Elanco Dairy Business Unit.
- Bartzis J.G., Vlachogiannis D., Sfetsos A. 2004. Thematic area 5: Best practice advice for environmental flows. *QNET-CFD Network News!* 2:34-9.
- Bava L., Tamburini A., Penati C., Riva E., Mattachini G., Provolo G., Sandrucci A. 2012. Effects of feeding frequency and environmental conditions on dry matter intake, milk yield and behaviour of dairy cows milked in conventional or automatic milking systems. *Ital. J. Animal Sci.* 11:230-5.
- Berman A. 2008. Increasing heat stress relief produced by coupled coat wetting and forced ventilation. *J. Dairy Sci.* 91:4571-8.
- Berman A. 2010. Forced heat loss from body surface reduces heat flow to body surface. *J. Dairy Sci.* 93:242-8.
- Bjerg B., Norton T., Banhazi T., Zhang G., Bartzanas T., Liberati P., Cascone G., Lee I.B., Marucci A. 2013. Modelling of ammonia emissions from naturally ventilated livestock buildings: Part 1, ammonia release modelling. *Biosyst. Eng.* 116:232-45.
- Bjerg B.S., Wang X., Zhang G. 2016. The effect of air velocity on heat stress at increased air temperature. Paper presented at CIGR - AgEng conference, Aarhus, Denmark.
- Bournet P.E., Boulard T. 2010. Effect of ventilator configuration on the distributed climate of greenhouses: a review of experimental and CFD studies. *Comput. Electr. Agric.* 94:47-57.
- Cascone G., Failla A., D'Emilio A., Porto S.M.C. 2004. Classificazione tipologica e ipotesi di riorganizzazione funzionale delle stalle per bovine da latte nell'area iblea. *Tecn. Agric.* 3-4.
- Chen X.Y., Zheng B., Hou K.M. 2012. *Building design and natural ventilation*. China Power Press, Beijing, China.
- Cook N.B., Mentink R.L., Bennett T.B., Burgi K. 2007. The effect of heat stress and lameness on time budgets of lactating dairy cows. *J. Dairy Sci.* 90:1674-82.
- Davis S., Mader T.L. 2003. Adjustments for wind speed and solar radiation to the temperature-humidity index. *Nebraska Beef Cattle Rep.* 224.
- D'Emilio A., Porto S.M.C., Cascone G., Bella M., Gulino M. 2017. Mitigating heat stress of dairy cows bred in a free-stall barn by sprinkler systems coupled with forced ventilation. *J. Agric. Eng.* 2017:691.
- D'Emilio A., Cascone G., Lanteri P., Porto S.M.C. 2018. Effects of different cooling systems on heat stress and behaviour of dairy cows. *CIGR Journal*.
- DeVries T.J., von Keyserlingk M.A.G., Weary D.M., Beauchemin K.A. 2003. Technical note: validation of a system for monitoring feeding behavior of dairy cows. *J. Dairy Sci.* 86:3571-4.
- DeVries T.J., Von Keyserlingk M.A.G., Weary D.M. 2004. Effect of feeding space on the inter-cow distance, aggression, and feeding behavior of free-stall housed lactating dairy cows. *J. Dairy Sci.* 87:1432-8.
- Etheridge D. 2015. A perspective on fifty years of natural ventilation research. *Build Environ.* 91:51-60.
- Fagundes B., Damasceno F., Andrade R., Obando F., Alexander J., Barbari M., Nascimento J. 2020. Comparison of airflow homogeneity in Compost Dairy Barns with different ventilation systems using the CFD model. *Agron. Res.* 18:788.
- Fournel S., Ouellet V., Charbonneau E. 2017. Practices for alleviating heat stress of dairy cows in humid continental climates: a literature review. *Animals.* 7:37.
- Gaspari J., Fabbri K., Cancellari T., Corazzi G., Vodola V. 2017. The use of building performance simulation to support architectural design: a case study. *Procedia Eng.* 121:205-10.
- Guo W., Liu X., Yuan X. 2015a. A case study on optimization of building design based on CFD simulation technology of wind environment. *Procedia Eng.* 121:225-31.
- Guo W., Liu X., Yuan X. 2015b. Study on natural ventilation design optimization based on CFD simulation for green buildings. *Procedia Eng.* 121:573-81.
- Kadzere C.T., Murphy M.R., Silanikove N., Maltz E. 2002. Heat stress in lactating dairy cows: a review. *Livestock Prod. Sci.* 77:59-91.
- Méndez C., San José J.F., Villafruela J.M., Castro F. 2008. Optimization of a hospital room by means of CFD for more efficient ventilation. *Energ. Buildings.* 40:849-54.
- Norton T., Sun D.W., Grant J., Fallon R., Dodd V. 2007. Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: a review. *Bioresour. Technol.* 98:2386-414.
- O'Driscoll K., Boyle L., Hanlon A. 2009. The effect of breed and housing system on dairy cow feeding and lying behaviour. *Appl. Animal Behav. Sci.* 116:156-62.
- Porto S.M.C., D'Emilio A., Cascone G. 2017. On the influence of the alternation of two different cooling systems on dairy cow daily activities. *J. Agric. Eng.* 2017:577.
- Provolo G., Riva E. 2009. One year study of lying and standing behaviour of dairy in freestall barn in Italy. *J. Agric. Eng. Res.* 40:27-33.
- Ruzal M., Shinder D., Malka I., Yahav S. 2011. Ventilation plays an important role in hens' egg production at high ambient temperature. *Poult. Sci. J.* 90:856-62.
- Shen X., Zhang G., Wu W., Bjerg B. 2013. Model-based control of natural ventilation in dairy buildings. *Comput. Electron. Agr.* 94:47-57.
- Seo I.H., Lee I.B., Moon O.K., Kim H.T., Hwang H.S., Hong S.W.,

- Bitog J.P., Yoo J.I., Kwon K.S., Kim Y.H., Han J.W. 2009. Improvement of the ventilation system of a naturally ventilated broiler house in the cold season using computational simulations. *Biosyst. Eng.* 104:106-17.
- Dati SIAS. 2016. Available online: www.sias.regione.sicilia.it Accessed: 15 April 2018.
- Song J., Meng X., 2015. The improvement of ventilation design in school buildings using CFD simulation. *Procedia Eng.* 121:1475-81.
- Tomasello N., Valenti F., Cascone G., Porto S.M.C. 2019. Development of a CFD model to simulate natural ventilation in a semi-open free-stall barn for dairy cows. *Buildings* 9:183.
- Vanhoudt A., Van Winden S., Fishwick J.C., Bell N.J. 2015. Monitoring cow comfort and rumen health indices in a cubicle-housed herd with an automatic milking system: A repeated measures approach. *Ir. Vet. J.* 68:368-762.
- Vilela M.O., Gates R.S., Martins M.A., Barbari M., Conti L., Rossi L., Zolnier S., Teles Jr C.G.S., Zanetoni H.H.R., Andrade R.R., Tinôco I.F.F. 2019. Computational fluids dynamics (CFD) in the spatial distribution of air velocity in prototype designed for animal experimentation in controlled environments. *Agron. Res.* 17:890-9

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