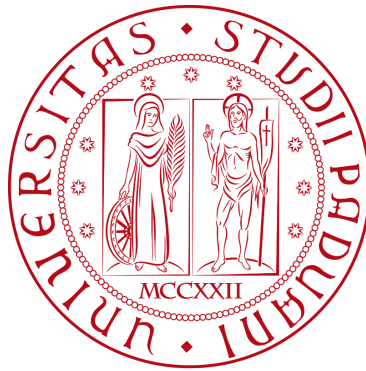




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Monitoring and dynamic energy simulations of cattle barns with envelope-embedded agricultural by-products

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Abstract

This thesis investigates the thermal and environmental performance of a naturally ventilated dairy cattle barn, with the aim of evaluating the potential influence of envelope materials incorporating Agricultural By-Products. Cattle are particularly sensitive to heat stress; therefore, the study focuses on assessing indoor thermal conditions rather than directly quantifying animal welfare improvements.

The research is structured in three main phases. The first phase consists of an experimental monitoring campaign, during which indoor environmental parameters such as air temperature, relative humidity, and CO₂ concentration were continuously measured using multiple sensors installed within the barn.

In the second phase, the collected data were analysed to characterize the indoor environment and to identify differences among the main thermal zones of the building.

In the final phase, a dynamic model of the barn was developed using TRNSYS coupled with CONTAM, enabling the simulation of both thermal behaviour and airflow patterns. The model was calibrated and validated against measured data according to standard statistical indicators. Subsequently, different envelope configurations were analysed by introducing materials based on Grape pomace (GP) with varying concentrations and insulation thicknesses.

The results, evaluated through the Temperature Humidity Index (THI), show that the use of ABPs-based materials leads to limited but consistent variations in indoor thermal conditions. Among the analysed configurations, the combination of P800 with a 7.5% GP layer provides the best overall performance, reducing heat stress exposure by up to 8 hours in the freestall area and 4 hours in the feeding alley over the analysed summer period.

The analysis also highlights a trade-off related to insulation thickness: reducing thickness decreases mild heat stress events, while increasing thickness improves performance under moderate stress conditions. However, the overall behaviour is mainly driven by the mild heat stress range, leading to slightly better performance for thinner configurations.

Despite these improvements, the impact on total heat stress events remains relatively limited, indicating that envelope modifications alone have a secondary role compared to other factors, such as ventilation and internal heat gains.

Nevertheless, the use of bio-based materials represents a promising alternative to conventional solutions, particularly from a circular economy perspective, as it enables the valorisation of agricultural by-products and the reduction of waste. However, aspects related to durability, maintenance, and large-scale applicability should be further investigated.

Finally, the results highlight the need for future studies to assess the performance of these materials under different climatic and operational conditions, as the analysed case study represents a specific configuration that may not be fully representative of other livestock buildings.

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Introduction

At the time of writing this thesis, the world is experiencing a period of geopolitical instability characterized by conflicts and increasing competition for resources. These events highlight how strongly modern societies depend on limited natural resources and how economic and political dynamics are often closely connected to energy and material availability. At the same time, humanity is facing another global challenge that develops more gradually but with potentially long-lasting consequences: climate change. Unlike sudden events such as wars or economic crises, environmental degradation often occurs progressively, accumulating effects over time until critical thresholds are reached. Among the sectors contributing significantly to global greenhouse gas emissions, the agri-food sector plays a crucial role. In particular, livestock production is responsible for a considerable share of emissions and resource consumption worldwide. For this reason, improving the sustainability and efficiency of agricultural systems has become an important research priority. The global livestock sector significantly contributes to anthropogenic greenhouse gas emissions, accounting for approximately 14.5% of total emissions worldwide [6]. A considerable fraction of these emissions is associated with methane (CH_4), mainly produced through enteric fermentation in ruminants. However, the sector can also deliver a substantial share of the necessary mitigation effort. The need to reduce its environmental footprint has become increasingly pressing, particularly in light of its ongoing expansion to ensure food security for a growing global population.

Despite the growing interest in improving the sustainability of livestock buildings, limited studies have focused on the dynamic interaction between building envelope properties and indoor environmental conditions in naturally ventilated dairy barns. In particular, the combined use of thermal and airflow simulation tools to reproduce the complex behaviour of such systems remains relatively unexplored. Moreover, the potential of agricultural by-products as building materials in this context has not been extensively investigated, especially in relation to their impact on animal thermal comfort.

The aim of this study is to develop and validate a dynamic model of a naturally ventilated dairy barn by coupling thermal and airflow simulations. The model is used to evaluate the impact of different building envelope configurations, including bio-based materials derived from agricultural by-products, on indoor environmental conditions and animal thermal comfort, assessed through the Temperature–Humidity Index (THI).

In this context, Agricultural By-Products are considered as raw materials for building envelope components. These materials can enhance the thermal performance of rural buildings while simultaneously promoting circular economy practices through the reuse of agricultural waste products. The bioeconomy encompasses a wide range of activities based on the use of renewable biological resources to produce materials, energy and services, contributing significantly to economic value and employment in the European Union [7].

In this study, the potential benefits associated with the use of these materials are evaluated by considering animal welfare as a key indicator. In particular, improving the thermal behaviour of the building envelope can contribute to more stable indoor environmental conditions, which play a crucial role in the well-being of animals housed in rural buildings.

The structure of the thesis is organised as follows:

Chapter 1 provides the theoretical background on dairy cattle thermal comfort, heat stress mechanisms, and the main indicators used for its assessment, with particular attention to the THI. It also introduces building envelope materials, including bio-based solutions, and presents the fundamentals of natural ventilation in livestock buildings.

Chapter 2 describes the case study of the analysed barn and the experimental monitoring campaign, including the building characteristics, the internal layout, and the monitoring system with sensor technical specifications and placement.

Chapter 3 focuses on data processing and zone identification. In particular, thermal zones are defined based on temperature and CO₂ concentration analyses. A descriptive analysis of the monitored climatic variables, including temperature, relative humidity, humidity ratio, and CO₂ concentration, is also presented.

Chapter 4 presents the development of the dynamic model of the barn. It includes the definition of thermal zones, the modelling approach in TRNSYS (Type 56), the airflow modelling in CONTAM, and the coupling procedure between the two tools. The chapter also discusses model calibration and validation.

Chapter 5 reports the simulation results. Both winter and summer conditions are analysed, with a detailed assessment of heat stress in the feeding alley and freestall areas. The chapter also investigates the effect of material properties and insulation thickness on the thermal performance of the barn.

Finally, Chapter 6 summarises the main findings of the study, highlights its limitations, and provides recommendations for future research.

Chapter 1

Background

1.1 Dairy cows and animal thermal comfort

The aim of the present study is to analyse the thermal behaviour of a cattle barn and to evaluate the performance of agricultural by-products used as building envelope materials. In order to achieve this objective, it is first necessary to assess the environmental conditions inside the barn and their influence on animal welfare. Unlike humans, animals cannot provide direct feedback about their comfort conditions. For this reason, several approaches have been developed to evaluate animal welfare. One of the most widely used is the *functional approach*, which is based on the proper functioning of biological systems. According to this approach, reduced welfare conditions are generally associated with the presence of diseases, injuries, malnutrition or physiological stress. Conversely, good welfare conditions are typically associated with high levels of growth, fertility and production quality. In order to guarantee good welfare conditions, the farmer must minimise the sources of stress that animals may experience, ensuring that the environment is as suitable as possible. In livestock production systems, animal welfare is commonly evaluated considering several criteria [8]:

- **Thermal welfare:** the environment should not be excessively hot or cold, as extreme temperatures may cause discomfort and reduce productivity.
- **Physical welfare:** the available space and the surfaces with which animals come into contact should prevent injuries and chronic discomfort.
- **Health control:** the environment should minimise the occurrence and spread of diseases while reducing stress factors that may weaken the immune system.
- **Behavioural welfare:** animals should be able to express their natural behaviours and social interactions, while also being reasonably free from fear.
- **Nutritional welfare:** animals should have easy access to feed and water, with nutrient intake properly balanced according to their physiological needs.

In the present study, the analysis focuses specifically on thermal welfare, as this is the aspect that can be directly influenced through the design and performance of the building envelope and the indoor environmental conditions.

1.1.1 Thermal welfare and heat stress

The thermoneutral zone (TNZ) of dairy animals ranges from 16°C to 25°C, within which they maintain a physiological body temperature of 38.4–39.1°C [9]. Outside this thermoneutral zone, animals experience thermal stress. The physiological (e.g., respiration rate) and behavioural (e.g., resting patterns) responses of dairy cows contribute to maintaining a stable body temperature by regulating their thermal energy balance, so that heat production through metabolism (maintenance, exercise, growth, lactation, gestation, and feeding) is balanced by heat loss to the environment (by conduction, convection, and evaporation) [10, 11]. The most critical condition for dairy cows occurs during warm weather, when the animal is no longer able to effectively dissipate body heat and may enter a state of heat stress (HS) which is characterised by an increase in respiratory rate, rectal temperature, and body surface temperature. Heat Stress is considered one of the main factors limiting productivity in dairy farming, as it negatively affects milk yield, feed intake, and overall animal performance. In general, Heat Stress increases body temperature and activates the hypothalamus–pituitary axis, causing increased water consumption and consequently a decrease in dry matter intake, resulting in weight loss and delay in body development, as shown in Table 1.1. Heat Stress can also lead to death in extreme cases [12]. In cattle production, severe thermal stress can decrease milk production and delay weight gain

Table 1.1: Behavioural changes in cattle occurring with heat stress[3]

Behaviour parameters	Association	
	Increase	Decrease
Feed intake		+++
Dry matter intake		+++
Feeding time	+	+
Time spent drinking	+++	
Drinking events	+	
Lying time		+++
Lying bouts	+	
Time spent standing	+++	
Locomotion		++
Aggressive interactions	+	
Vocalisation	+	
Shade seeking	+++	
Seeking areas with optimal ventilation	++	

slight [+], moderate [++], or strong [+++] association;

+* = Dependent on milk yield of cows.

[13]. The effects of climate variables such as air temperature, wind speed, relative humidity, and solar radiation can negatively affect animals, especially cattle exposed to direct solar radiation [14, 15]. Therefore, environmental conditions inside livestock buildings must be properly controlled in order to ensure animal welfare and maintain adequate production performance. Figure 1.1 shows the relationship between environmental temperature and body temperature in dairy cattle. Within the thermoneutral zone (TNZ), animals are able to maintain a stable body

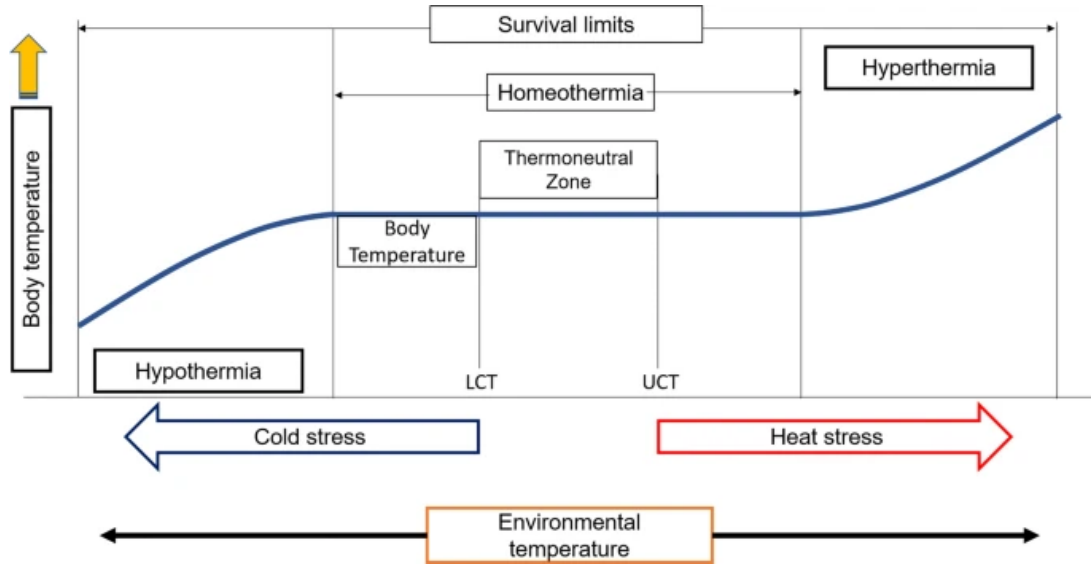


Figure 1.1: Body temperature variation with an increase or decrease in environmental temperature. LCT is the lower critical temperature, and UCT is the upper critical temperature[1]

temperature (homeothermia) through physiological and behavioural responses without significant additional energy expenditure. Outside this range, the animal experiences thermal stress. At low environmental temperatures, heat loss exceeds heat production, leading to cold stress and, in extreme conditions, hypothermia. Conversely, at high environmental temperatures, the animal is no longer able to effectively dissipate metabolic heat, resulting in heat stress and potentially hyperthermia. The limits of the thermoneutral zone are defined by the lower critical temperature (LCT) and the upper critical temperature (UCT), which represent the thresholds beyond which the animal must activate additional mechanisms to maintain thermal balance.

1.1.2 Thermal balance modelling of dairy cattle

The thermal balance of cattle is defined by energy conservation, while literature studies provide correlations and models to quantify the different heat exchange mechanisms with the environment, including conduction, convection, evaporation and radiation. Some models also include heat conduction between the animal and the ground surface when the animal lies down, whereas previous models did not consider this component. Although cows under heat stress tend to stand rather than lie down, lying behaviour still accounts for about one third of the total daily time budget for dairy cows during summer. For this reason, it is necessary to include this contribution in the thermal balance [4].

The heat production (HE) can be roughly estimated using the following empirical equation [16] when detailed dietary information is not available:

$$HE = \frac{c_h BW^{0.75}}{3.6} \quad (1.1)$$

where c_h is an empirical coefficient depending on the production level, equal to 44.1 for high-production cows (daily milk yield > 30 kg), 37.8 for intermediate-production cows (daily

milk yield < 30 kg), and 29.7 for dry cows. BW [kg] is the body weight of the animal. The relative contribution of the different heat exchange mechanisms during the day is summarised in Table 1.2.

Table 1.2: The average percentage (%) of heat dissipation through convection, evaporation, long wave radiation, respiration and conduction between animal and ground surface during different time periods [4]

	00:00–06:00h	06:00–12:00h	12:00–18:00h	18:00–24:00h	Entire day
Convection	14.1	19.8	14.9	8.0	14.9
Evaporation	32.6	49.3	57.0	45.7	48.0
LW radiation	28.7	16.6	11.5	21.8	18.2
Respiration	15.9	13.8	16.6	19.7	16.2
Conduction	8.7	0.5	–	4.8	2.7

1.1.3 Technique to reduce the heat stress

To reduce the negative effects of heat stress on dairy cattle, farmers can act on several aspects:

- Selection of heat-tolerant cattle breeds
- Nutritional management and feeding strategies
- Modification of the barn environment

Among these strategies, environmental modification is considered one of the most effective approaches for mitigating heat stress in dairy cattle [17]. This category can be further divided into two main approaches:

- Active control
- Passive control

Active control strategies aim to enhance heat dissipation from the animals by increasing evaporative cooling and convective heat transfer. Evaporative cooling can be achieved by wetting the cows or the surrounding air through systems such as misters and sprinklers, while convective heat transfer can be increased by raising the air velocity around the animals using fans. These techniques generally rely on forced ventilation systems, often combined with evaporative cooling technologies. Evaporation of water is an endothermic process and represents one of the most effective mechanisms for reducing the internal temperature of livestock buildings. Active cooling strategies generally rely on forced ventilation and evaporative cooling technologies. Several studies [8, 18] report a wide range of techniques for reducing heat stress in livestock buildings, including air conditioning systems, evaporative cooling devices (such as foggers, misters, and cooling pads), and mechanical ventilation systems (e.g., fans and tunnel ventilation).

Passive control strategies aim to reduce heat stress in cattle without the use of mechanical air conditioning systems, by acting on solar gains, natural ventilation, and the thermal mass of the building. Such strategies include, for example, the orientation of the barn, the thermal

inertia of the building, and the type of roof covering. However, these design-related solutions are generally more difficult to implement once the building has already been constructed. In contrast, other passive measures, such as natural ventilation and shading systems, can be more easily modified or integrated.

In this thesis, particular attention is given to the role of the building envelope, with a focus on the use of agricultural by-products (ABPs) as sustainable construction materials. These materials are investigated in the context of circular economy principles, promoting the reuse of agricultural waste. The objective is to evaluate the thermal performance of the building when these materials are applied to the envelope, and to assess their influence on indoor environmental conditions and animal welfare [8].

1.1.4 Monitoring the heat stress: the THI index

Monitoring environmental parameters is an important step in understanding how animals interact with the surrounding environment and the level of thermal stress they may experience. Understanding current or upcoming environmental conditions allows farmers to implement appropriate management strategies to mitigate heat stress. Four key environmental parameters mainly influence the thermal conditions perceived by livestock: air temperature, relative humidity, wind speed and solar radiation.

Over time, the cattle industry has adopted index-based heat stress thresholds that account either for environmental parameters (e.g., temperature humidity index, THI) or a combination of weather parameters and animal responses (e.g., heat load index, HLI). Therefore, several environmental indices have been proposed to evaluate heat stress in livestock. These indices differ mainly in the number of environmental variables considered and in the complexity of their formulation.

Table 1.3: Overview of dairy cow heat stress indices[5]

Index	Name of the index	Authors, publication year
THI	Temperature-humidity index	Thom 1959[19]; NRC 1971[20]
BGHI	Black globe-humidity index	Buffington et al. 1981 [21]
ETI	Equivalent temperature index	Baeta et al. 1987 [22]
HLI	Heat load index	Gaughan et al. 2003, 2008 [23, 24]
THIadj	Adjusted temperature humidity index	Mader et al. 2006 [25]
CCI	Comprehensive Climate Index	Mader et al. 2010 [26]
ITSC	Index of thermal stress for cows	Da Silva et al. 2015 [27]

Among the various indices proposed in the literature, the *Temperature Humidity Index* (THI) is the most widely used method for assessing heat stress in dairy cattle. This index combines air temperature and relative humidity into a single value representing the thermal conditions experienced by the animals. Due to its simplicity and the limited number of required environmental parameters, it is widely applied both in experimental studies and in practical farm management.

Despite its extensive use, the THI presents some limitations. The index only accounts for air temperature and relative humidity, neglecting other environmental variables such as solar radiation, wind speed and ventilation conditions, as well as animal-related factors. Consequently,

Table 1.4: Application and components of equations for the calculation of the indexes [5]

Index	Parameters					Maintenance system		Region of use	
	Ta	RH	V	SR	Tdp	Barn	Pasture	Tropical	Moderate
THI ^a	x	x			x	x	x	x	x
CCI	x	x	x	x		x	x	x	x
THIadj	x	x	x	x		x	x	x	x
ETI	x	x	x			x		x	
HLI		x	x				x	x	
BGHI					x		x	x	x
ITSC ^b	x		x				x	x	

Ta air temperature, [°C]; RH relative air humidity, [%]; V air velocity, [m/s]; SR intensity of solar radiation, [W/m²]; Tdp dew point temperature, [°C]; Tbg black globe temperature, [°C].

^a Different configuration of parameters: Ta with RH or Tdp.

^b ITSC additionally comprises: ERHL—effective radiation heat load, [W/m²] and Pv—partial vapour pressure, [kPa].

it may not fully represent the actual thermal load experienced by dairy cattle under specific microclimatic conditions. Nevertheless, because of its simplicity and widespread adoption in the literature, the THI remains a useful indicator for evaluating and comparing thermal conditions in livestock buildings.

Several formulations of the THI equation have been proposed in the literature, although they are all based on the combined effect of air temperature and humidity on thermal comfort.

Table 1.5: Formulas for calculating THI values [5]

Authors	Year	Calculation formula
Thom	1959	$THI = [0.4 \times (Tdb + Twb)] \times 1.8 + 32 + 15$
Bianca	1962	$THI = (0.35 \times Tdb + 0.65 \times Twb) \times 1.8 + 32$
Kibler ^a	1964	$THI = 1.8Tdb - (1 - RH)(Tdb - 14.3) + 32$
NRC	1971	$THI = (1.8 \times Tdb + 32) - (0.55 - 0.0055 \times RH)(1.8 \times Tdb - 26)$
Yousef	1985	$THI = Tdb + (0.36 \times Tdp) + 41.2$
Mader et al.	2006	$THI = (0.8 \times Tdb) + \left(\frac{RH}{100}\right)(Tdb - 14.4) + 46.4$

Tdb dry bulb air temperature, [°C]; Twb wet bulb air temperature, [°C]; Tdp dew point temperature, [°C]; RH relative air humidity, [%]. ^a In Kibler formula RH is expressed as a fraction.

THI is a dimensionless index widely used to assess heat stress conditions in dairy cattle. In general, higher THI values correspond to higher levels of thermal stress experienced by the animals. Although there is no universally fixed threshold, literature suggests that heat stress typically begins to occur within a range of approximately 68 to 74, depending on factors such as breed, productivity level, and environmental conditions. In particular, high-producing dairy cows may experience heat stress at lower THI values (around 60–68) [28, 29], while traditional thresholds often identify values above 72 as critical for the onset of performance reduction [30]. These discrepancies are mainly due to differences in climatic conditions, animal characteristics,

and the specific THI formulation adopted. In this study, THI is used as an indicator of the thermal conditions inside the barn and as a reference parameter to compare monitored and simulated environmental conditions.

Figure 1.2 shows an example of a THI classification chart, where different ranges of the index are associated with increasing levels of heat stress. In particular, threshold values are linked to alert, danger, and emergency conditions, providing a practical tool for farmers to identify critical situations and take appropriate mitigation measures.

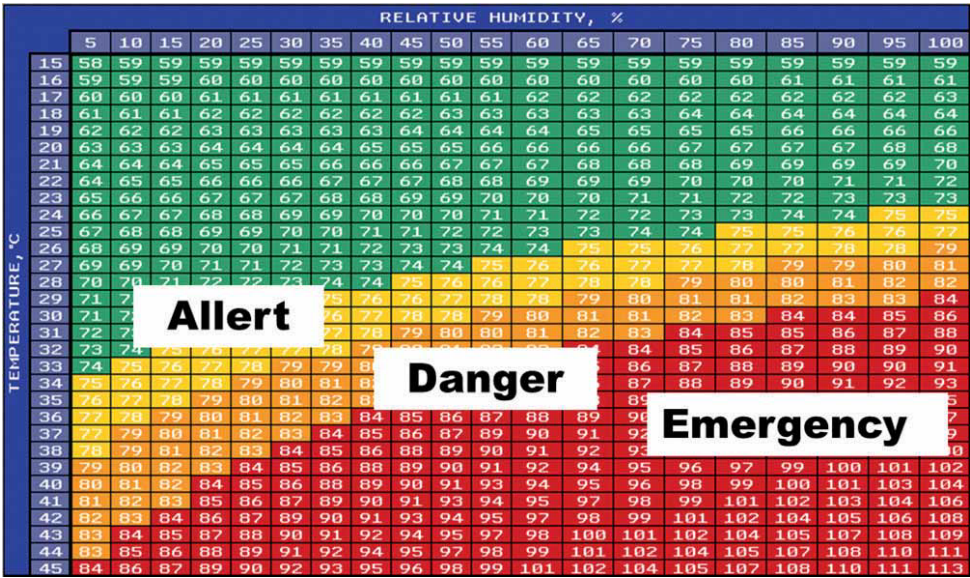


Figure 1.2: THI index graph[2]

1.2 Building envelope materials

The construction industry has significant environmental, social and economic impacts on society. In this regard, a distinction can be made between the positive and the negative impacts related to construction activities [31]. In particular, the former include providing buildings and infrastructure able to satisfy human needs, creating employment opportunities both directly and indirectly through industries related to the construction sector, and contributing to national economic development [32].

On the other hand, construction practices are widely recognised as major contributors to environmental concerns, mainly due to the high consumption of energy, often derived from non-renewable sources, and the extensive use of non-renewable materials. At a global level, civil works and building construction consume about 60% of the raw materials extracted from the lithosphere. Buildings alone account for approximately 40% of this amount, corresponding to about 24% of global extractions [33].

Furthermore, the manufacture, transport and installation of materials commonly used in buildings, such as steel, concrete and glass, require large amounts of energy, despite representing only a small fraction of the total economic cost of the building. This apparent contradiction is known as the “Rule of the Notary” [34].

For this reason, it is essential to direct the development of the building sector towards more environmentally sustainable solutions in order to address the challenges related to energy consumption, climate change and resource depletion [31]. In this context, it becomes necessary to promote the use of the best available techniques and technological innovation in production processes, as well as to progressively replace the use of finite natural resources with waste generated in different industrial processes, thus contributing to the closing of material cycles.

This approach requires a strong commitment to reuse and recycling practices, while minimising the transport of raw materials and final products and promoting the use of locally available resources [34].

1.2.1 Bio-based building materials

One of the most relevant locally available resources in Mediterranean countries is vine cultivation, which represents one of the most widespread agricultural activities worldwide [35, 36]. This large-scale production generates a significant amount of waste, commonly referred to as Grape pomace (GP). The countries with the highest production of GP are Italy, France and Spain, with approximately 1.4, 1.2 and 1 million tonnes per year, respectively (OIV, www.oiv.int).

It is generated after pressing the grapes in white wine production, or after fermentation and maceration processes in the case of red wines. In fact, it is a complex lignocellulosic material whose chemical composition varies significantly depending on the grape variety [37]. Traditionally, GP has been used as fertiliser, animal feed or for the production of distillates. More recently, it has also been investigated as a potential biofuel due to its high calorific value. However, alternative applications aimed at material recovery are gaining increasing attention.

GP consists mainly of grape skins, seeds, stems and wine lees [38]. The use of such agricultural by-products in building materials represents a promising strategy to reduce the environmental impact of the construction sector, contributing to lower CO₂ emissions and promoting circular economy principles.

In particular, several studies have investigated the incorporation of GP as an additive in building materials, showing improvements in thermal insulation properties as a result of increased porosity, while maintaining acceptable mechanical performance within certain percentage limits [39, 40].

However, in most conventional applications, these materials are subjected to high temperature firing processes, which involve significant energy consumption. For this reason, increasing attention is being devoted to the development of unfired bio-based materials, which can significantly reduce the embodied energy associated with building components [38]. This approach represents an innovative extension of circular economy principles, enabling the transformation of high-impact agri-food waste into low-carbon, recyclable and high-performance earthen composites [41].

1.2.2 Description of the unfired bio-based material

The material used to evaluate the thermal insulation performance of the barn through modelling consists of unfired clay blocks incorporating Grape pomace (GP). This material differs from those investigated in previous studies, which have mainly focused on fired clay products [41].

The simulations were carried out considering five different concentrations of (GP), equal to 0%, 2.5%, 5%, 7.5% and 10% by weight. The soil matrix is composed of 15% clay, 25% silt and 60% sand, with a water content of 20% by weight.

The main thermophysical properties of the analysed materials are summarised in Table 1.6. where λ is the thermal conductivity, c_p is the specific heat capacity, and ρ is the density.

	λ [kJ/(h m K)]	c_p [kJ/(kg K)]	ρ [kg/m ³]
ID_0	3.56	0.922	1950.96
ID_2.5GP	3.42	1.062	1632.86
ID_5GP	2.56	0.726	1783.45
ID_7.5GP	1.80	0.246	1857.51
ID_10_GP	0.90	0.270	1666.70

Table 1.6: Thermophysical properties of the analysed bio-based materials used in this study

1.3 Energy simulation of livestock buildings

The aim of this study is to develop a dynamic model of a dairy cattle barn in order to evaluate the thermal conditions experienced by the animals and assess whether modifications to the building envelope can improve indoor environmental quality and animal welfare.

Livestock buildings can operate either with mechanical ventilation systems or rely on natural ventilation, depending on the design and management strategy [18]. In naturally ventilated buildings, air exchange is mainly driven by wind and infiltration phenomena. In the present study, the analysed building operates without mechanical ventilation; therefore, air exchange is governed by natural ventilation and infiltration, which represent a key aspect of the modelling approach.

Dynamic energy simulations of livestock buildings are less common in the literature compared to residential and commercial applications. Most existing studies focus either on simplified thermal models or on specific aspects such as ventilation efficiency and heat stress evaluation, often without a fully coupled dynamic approach.

In this context, the combined use of TRNSYS and CONTAM represents a relevant methodological choice. TRNSYS is widely used for transient thermal simulations of buildings, while CONTAM allows detailed modelling of airflow. However, their coupling has been mainly applied to residential buildings, particularly for the analysis of indoor air quality and natural ventilation.

The application of this coupled approach to livestock buildings presents additional challenges. In particular, modelling natural ventilation in agricultural environments is complex due to the difficulty in accurately defining airflow paths and boundary conditions. For this reason, CONTAM is less frequently used in such contexts, where other modelling approaches or simplified assumptions are often preferred.

1.3.1 Natural ventilation in buildings

Natural ventilation and infiltration in buildings are driven by pressure differences across the building envelope, which originate from two main mechanisms: the stack effect and wind-induced pressure.

The stack effect is caused by temperature differences between indoor and outdoor air, leading to density gradients. When indoor air is warmer than outdoor air, buoyancy forces drive the upward movement of air within the building. As a result, warm air exits through higher openings, while cooler outdoor air enters through lower openings, establishing a vertical airflow pattern.

Wind-induced ventilation is generated by pressure differences on building surfaces due to wind action. These pressures depend on several factors, including wind speed and direction, building geometry, and surrounding environment. Typically, positive pressures occur on the windward side of the building, while negative pressures develop on the leeward side, promoting air exchange through openings and leakage paths.

In real conditions, natural ventilation is governed by the combined effect of stack and wind-driven forces. The resulting airflow rates are influenced by additional factors such as building height, internal airflow resistance, and the characteristics of openings and leakage paths [42].

1.3.2 Modelling approaches for natural ventilation

Several studies have investigated natural ventilation modelling through the coupling of thermal and airflow simulation tools, particularly TRNSYS and CONTAM. This combined approach allows the simultaneous evaluation of thermal behaviour and airflow dynamics under transient conditions.

Most of the existing applications of TRNSYS–CONTAM coupling focus on residential and commercial buildings. For instance, the study by Icaro et al. [43] analysed the effectiveness of ventilation strategies as a passive cooling technique (free cooling), showing how natural and mechanical ventilation can reduce the sensible heat load when outdoor conditions are favourable. In this context, ventilation plays a dual role: on the one hand, it contributes to thermal comfort, while on the other, it ensures indoor air quality (IAQ), which remains a fundamental requirement in building design. Similarly, Khalifa et al. [44] applied the coupling of TRNSYS and CONTAM to the simulation of a naturally ventilated double-skin façade under Mediterranean climatic conditions. Their work demonstrated that this approach enables a detailed evaluation of the transient heat and mass transfer processes, providing reliable results when compared with experimental data. The study also highlighted the advantages of using airflow network models, which allow year-round simulations with reduced computational effort compared to CFD approaches. These studies confirm that the TRNSYS–CONTAM framework represents a robust and flexible tool for the analysis of naturally ventilated buildings. However, its application is mainly limited to standard building typologies, such as residential or office environments. In contrast, livestock buildings present additional challenges due to the higher magnitude and variability of internal sensible and latent heat loads, mainly associated with animal metabolism, as well as more complex and less predictable airflow patterns. Moreover, while simulations in civil buildings often address multiple aspects such as thermal comfort, indoor air quality and energy performance, in livestock environments the focus shifts towards animal welfare, which is typically evaluated through specific indices such as the Temperature Humidity Index.

For these reasons, the application of coupled thermal–airflow models to agricultural buildings remains limited in the literature, particularly in the case of naturally ventilated livestock environments. This study aims to address this gap by applying a TRNSYS–CONTAM modelling approach to a dairy cattle barn, focusing on the evaluation of indoor thermal and hygrometric conditions and their impact on animal well-being through appropriate comfort indices.

Chapter 2

Case study and instrumentation

2.1 La Negritella's cattle barn

The case study is located in Moena (TN), in the Dolomites, a mountainous region in Northern Italy, at an altitude of approximately 1800 m above sea level. The site is situated near Passo San Pellegrino. Inside the barn, dairy cows are housed, mainly belonging to two breeds: Holstein



Figure 2.1: External view of the La Negritella cattle barn (source: Google Maps)

(Friesian) and Brown Swiss. The facility is equipped with automated systems for feeding, cleaning, and animal management. The animals remain inside the barn throughout the year, except during calving periods, when they are moved to a separate structure. The herd size varies between 50 and 60 animals, with an average body weight ranging from 500 kg to 800 kg. The cows are older than two years and are classified by the farmer as medium-production animals, with an average milk yield of 30–35 *L/day*. The monitoring campaign carried out in this study lasted four weeks.

As shown in Figure 2.2, the barn layout is divided into two main areas: a service zone dedicated to human activities and a zone dedicated to the animals. The figure also highlights

the orientation of the building, which is relevant for the subsequent analyses carried out in this study. The main functional areas, reported in Italian in the figure, are:

- Feed delivery alley (*corsia di foraggiamento*)
- Feeding alley (*corsia di alimentazione*)
- Freestalls (*cucette*)
- Technical area (*zona tecnica*)

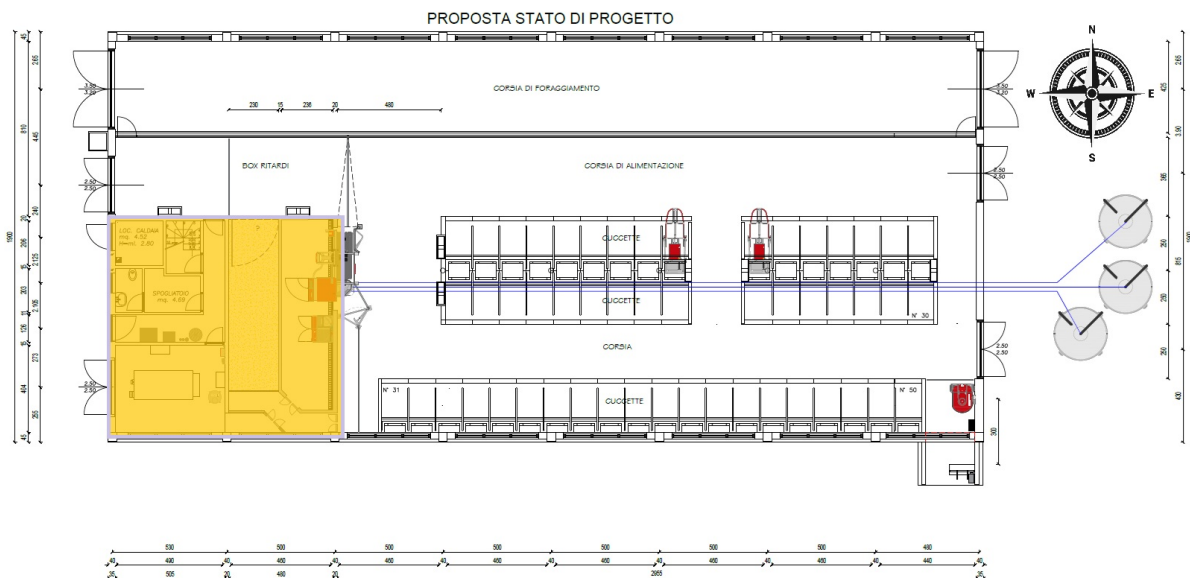


Figure 2.2: Layout of the La Negritella dairy cattle barn. The area highlighted in yellow represents the portion excluded from the analysis due to the lack of available information.

Due to the lack of available information, the technical area was not included in the analysis, as shown in Figure 2.2. The barn is naturally ventilated through a continuous roof ridge opening running along the entire length of the structure (Figure 2.5c and 2.6). Furthermore, data acquisition devices were installed up to the beginning of the separation pen (*box ritardi*). Consequently, the monitoring campaign covers only this portion of the barn, while areas beyond this point were not instrumented. Openings and other physical elements located within the monitored area were documented for the subsequent analysis.

2.1.1 Building envelope characteristics

The building envelope is characterized by the presence of additional materials applied to both the walls and the roof. The Poroton P800 is a prefabricated clay block commonly used for wall construction in agricultural buildings. In the considered configuration, it represents the structural component of the wall, while the overall thermal performance is enhanced by the addition of an external insulating layer. The wall insulation is characterized by the following layered structure:

Table 2.1: Thermal resistance of the wall insulation system

#	Material	Thickness [cm]	λ [W/mK]	R [m ² K/W]
1	Plasterboard panel	1.25	0.250	0.050
2	OSB3	1.50	0.130	0.115
3	PE layer	0.20	0.400	0.005
4	Mineral wool 035	10.00	0.035	2.857
4	Fir wood (9.1%)	10.00	0.130	0.769
5	OSB3	1.50	0.130	0.115

The overall thermal resistance was calculated by summing the contribution of each layer in accordance with DIN EN ISO 6946 [45].

The wall stratigraphy presented in Table 2.1 represents the reference configuration of the wall. Figure 2.3 illustrates the geometrical configuration of the wall layers, providing a visual representation of the materials.

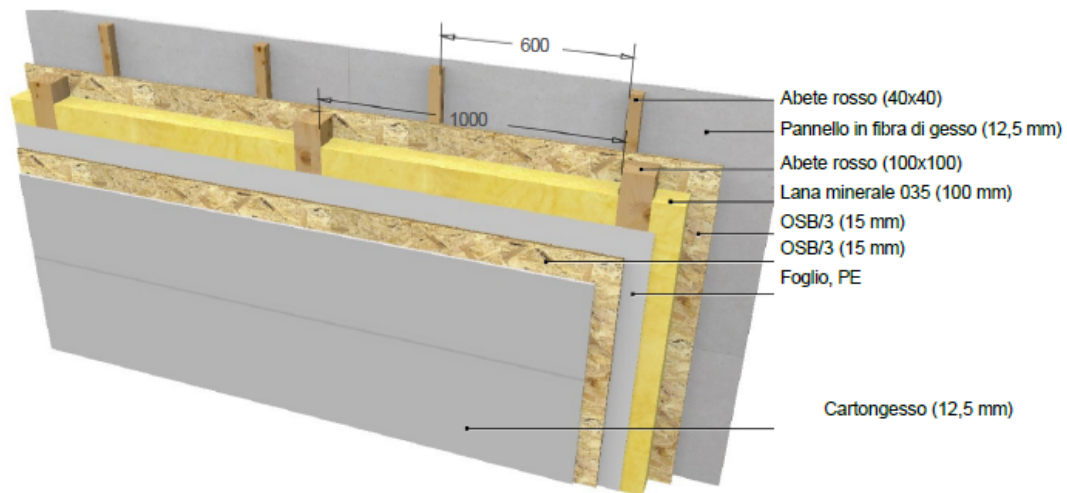


Figure 2.3: Layered configuration of the wall insulation system

The roof insulation is characterized by the following layered structure:

Table 2.2: Thermal resistance of the roof insulation system

#	Material	Thickness [cm]	λ [W/mK]	R [m ² K/W]
1	Profiled wood (tongue and groove)	2.10	0.130	0.162
2	Vapour barrier (sd = 0.1 m)	0.05	0.220	0.002
3	Glass wool (WLG040)	10.00	0.040	2.500
4	Air layer (still air)	60.00	3.026	0.198
4	Fir wood (8.3%)	60.00	0.130	4.615
5	Profiled wood (fir/spruce)	2.40	0.140	0.171
6	Under-roof membrane (sd = 0.1 m)	0.05	0.500	0.001
7	Beams (fir wood)	5.00	0.130	0.385
7	Rear ventilation (external air, 94%)	5.00	0.313	0.160
8	Beams (fir wood)	5.00	0.130	0.385
8	Rear ventilation (external air, 94%)	5.00	0.313	0.160
9	Trapezoidal sheet metal	2.80	10.000	0.003

The roof presents a more complex structure compared to the walls, due to the presence of ventilated layers and structural discontinuities as shown in Figure 2.6. The stratigraphy used for the roof is reported in Table 2.2.

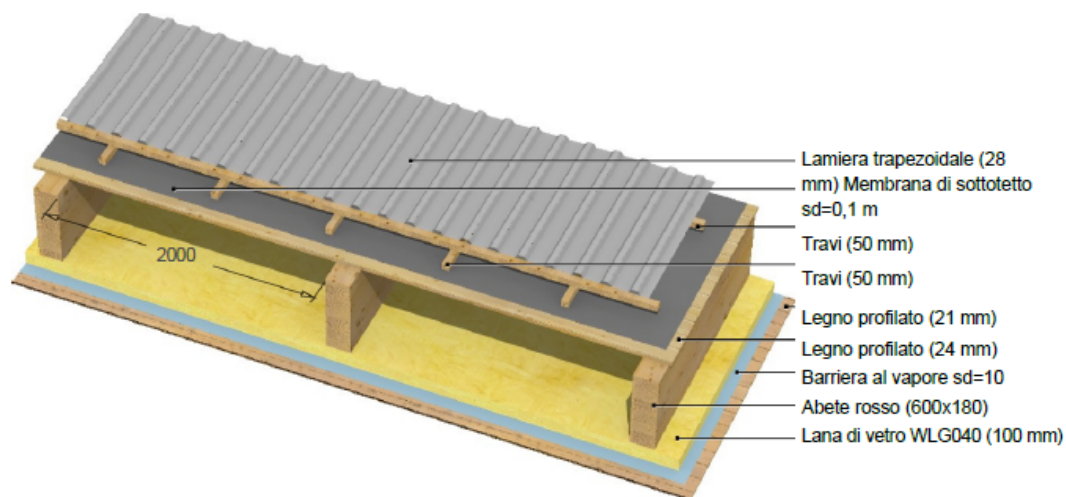


Figure 2.4: Layered configuration of the roof insulation system

2.1.2 Barn layout and internal organization



Figure 2.5: Internal areas of the cattle barn.

The floor of the *Feed delivery alley* (Figure 2.5a), where both personnel and agricultural machinery operate, is made of concrete. The external wall of this area includes 24 windows, arranged in eight groups of three. At the eastern end of the barn, an overhead door is installed, which is opened and closed a few times per day (approximately 2–3 times). At the western end, a wooden door of the same dimensions is present. A metal grate acts as a structural separation between the Feed delivery alley and the feeding alley.

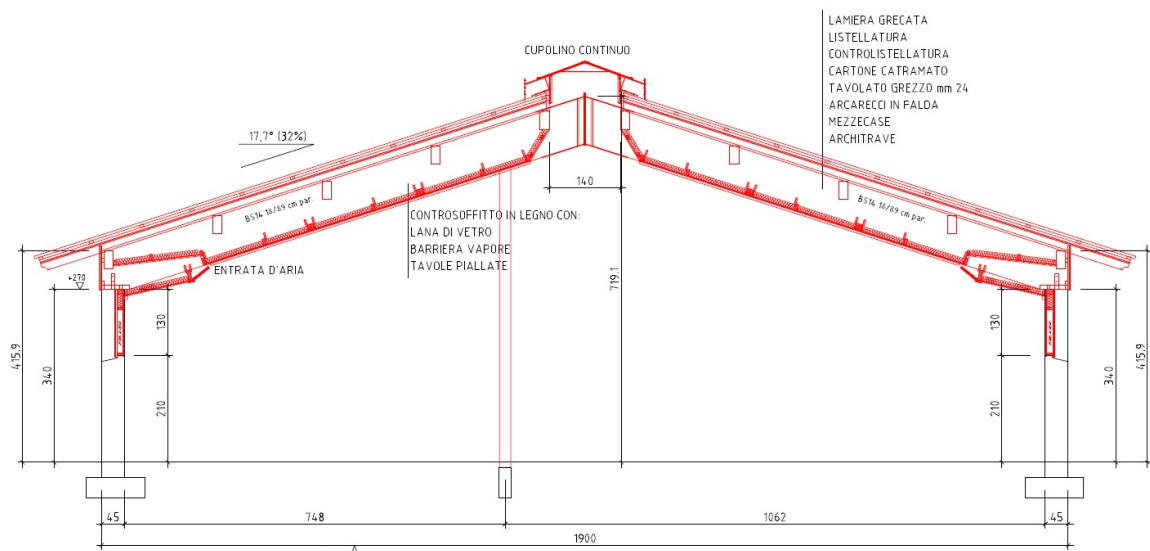


Figure 2.6: Cross-sectional view of the cattle barn highlighting the roof structure and natural ventilation system.

In the *animal area* (Figure 2.5b), the floor consists of two different types. The walking area is made of concrete covered with a layer of vulcanized rubber, while the freestalls consist of an additional concrete layer topped with straw bedding. The freestalls are designed to improve animal comfort and to guide the animals' movement, allowing them to enter and exit without

turning around. This design reduces the likelihood of soiling the resting area. The boundaries of the *animal area* consist of three wooden doors, which are always kept closed (two on the east side and one on the west side). On the south side, there are 18 windows arranged in six groups, while an additional window is located on the west side as shown in Figure 2.7. Within this area, an automated cleaning system removes manure and transports it to a manure storage area located at the south-east edge of the building. In addition, the barn is equipped with two automatic feeders, an automatic milking system, and a mechanical brush used to improve animal welfare. Figure 2.7 and 2.6 show the external view of the barn and its main façade.



Figure 2.7: External view of the La Negritella dairy cattle barn

2.2 Monitoring system

The monitoring campaign was carried out using three different types of sensors. Two of them were able to measure air temperature, relative humidity and CO₂ concentration, while the third one measured only air temperature and relative humidity. The sensors used in the study are listed below:

- *MX1102* (Onset HOB0) [46]: 4 devices, Figure 2.8a
- *MX1104* (Onset HOB0) [46]: 4 devices, Figure 2.8b
- *Aranet4* – 400E9D (Aranet4 CO₂ sensor) [47]: 1 device, Figure 2.8c

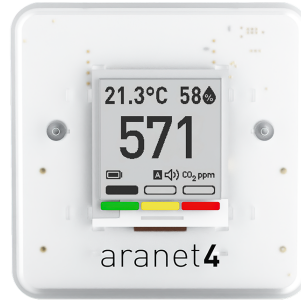
The aim of the monitoring campaign was to collect indoor environmental data, including air temperature, relative humidity, and CO₂ concentration, in order to analyse the thermal be-



(a) MX1102 data logger



(b) MX1104 data logger



(c) Aranet4 CO₂ sensor

Figure 2.8: Monitoring devices used in the study.

haviour of the barn and the environmental conditions experienced by the animals. These data were subsequently used to support the development and validation of a numerical model.

The data acquisition started on November 7th and ended on December 12th, with a time step of 5 minutes. Before installation in the monitoring area, only the CO₂ sensors were calibrated by placing them in a controlled environment with a CO₂ concentration close to ambient outdoor levels for 5 minutes.

2.2.1 Technical specifications

The main technical specifications of the monitoring devices are summarized in the following tables:

Table 2.3: Technical specifications of the Aranet sensor

Parameter	CO ₂	Temperature	Relative Humidity	Pressure
Range	0–9999 ppm	0–50 °C	0–85 %	600–1100 hPa
Resolution	1 ppm	0.1 °C	1 %	1 hPa
Accuracy	±(30 ppm + 3% of reading)	±0.3 °C	±3 %	+3 / -2 hPa
Long-term drift	–	0.03 °C/year	0.5 %/year	1 hPa/year
Time constant τ	100 s	10 min	6 min	0 s

It should be noted that the measurement time constant of the temperature sensor (approximately 10 minutes) is higher than the selected acquisition time step (5 minutes). Therefore,

consecutive measurements are not fully independent, and high-frequency fluctuations may be attenuated. However, this limitation is considered acceptable in the present case, as the barn is naturally ventilated but characterized by relatively slow thermal dynamics, due to the continuous presence of animals and the fact that openings are generally kept closed for most of the time. The device also measures atmospheric pressure, as reported in Table 2.3. This variable is required for the calculation of humidity ratio inside the barn.

Table 2.4 reports the technical specifications of the HOBO sensor, which is able to measure not only temperature and relative humidity but also CO₂ concentration. It should be noted that the temperature sensor exhibits a relatively long response time (approximately 12 minutes), which may result in a smoothing of short-term fluctuations in the recorded data.

Table 2.4: Technical specifications of the HOBO MX1102 data logger

Parameter	CO ₂	Temperature	Relative Humidity
Range	0–5000 ppm	0–50 °C	1–90 %
Resolution	–	0.024 °C	0.01 %
Accuracy	±(50 ppm + 5% of reading)	±0.21 °C	±2% (20–80%)
Long-term drift	–	<0.1 °C/year	<1%/year
Time constant τ	~1 min	~12 min	~1 min

Table 2.5 shows the technical specifications of the HOBO sensor, which measures only temperature and relative humidity. The temperature sensor exhibits a response time of approximately 11 minutes, which is consistent with the other devices used in the monitoring campaign. This results in a similar dynamic response among the sensors and may lead to a general smoothing of short-term temperature fluctuations.

Table 2.5: Technical specifications of the HOBO MX1104 data logger

Parameter	Temperature	Relative Humidity
Range	-20–70 °C	0–100 %
Resolution	0.002 °C	0.01 %
Accuracy	±0.20 °C	±2.5% (10–90%)
Long-term drift	<0.1 °C/year	<1%/year
Time constant τ	~11 min	~30 s

The technical specifications reported in Tables 2.3, 2.4, and 2.5 are provided by the manufacturers. Each HOBO MX1104 and MX1102 device is supplied with a calibration certificate issued in compliance with LAT accreditation (No. 238), in accordance with Italian Law No. 273/1991 [48]. This certification ensures the reliability of the measured data.

2.2.2 Sensor placement

The sensors were distributed throughout the barn in order to cover all the internal areas and positioned at different heights to investigate the possible vertical stratification of air temperature and CO₂ concentration. All sensors were installed inside the barn, as their technical specifications limit their use in outdoor conditions, particularly due to operating temperature constraints

and exposure to climatic factors such as solar radiation, wind, and precipitation, as discussed in the previous section. For the characterization of the outdoor boundary conditions, meteorological data were obtained from an external environmental monitoring station managed by ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto), located at Passo Valles (Falcade, BL), in close proximity to the case study. The following variables were collected from the ARPAV station:

- *Air temperature*
- *Relative humidity*
- *Solar irradiance on the horizontal plane*
- *Wind speed*
- *Wind direction*

Since the main focus of the study is the assessment of animal welfare, a higher number of sensors was installed within the animal area, while only one sensor was placed in the feed delivery alley (blue marker). A total of eight sensors were deployed: six at a height of approximately 3 m and two near ground level (purple and grey markers). As shown in Figure 2.9, four sensors installed at a height of 3 m were positioned along the central axis of the animal area, in correspondence with the freestalls (green, pink, red, and yellow markers). The remaining two sensors were located in the feeding alley, arranged along a line perpendicular to the main longitudinal axis of the barn (black and orange markers). The decision to install most of the sensors

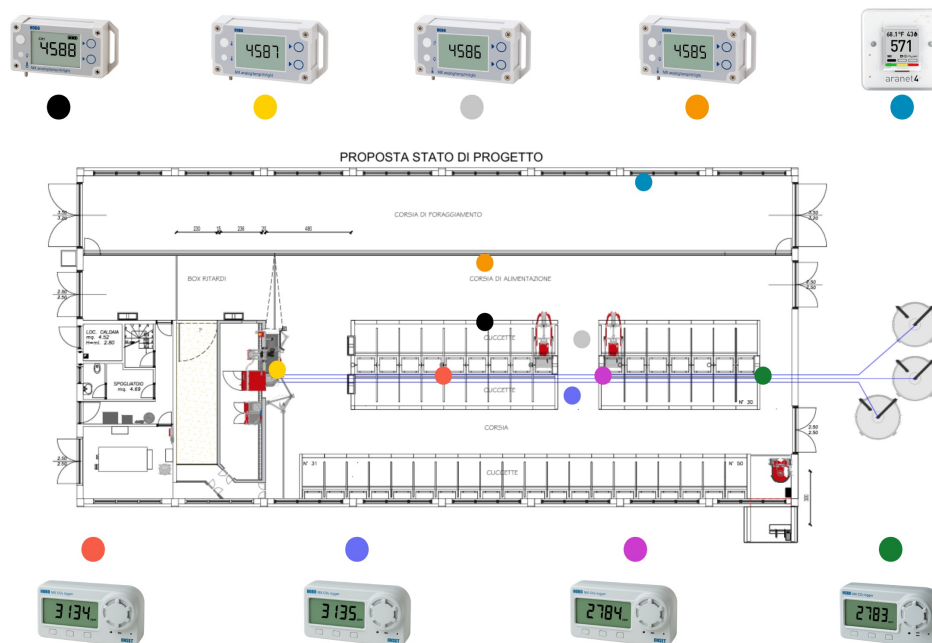


Figure 2.9: Layout of the sensor positions inside the cattle barn. Each device is shown with its display, where the identification number corresponding to the actual serial number is reported.

at a higher positions was driven not only by practical considerations but also by the behavior of the animals, which tend to interact with unfamiliar objects. For this reason, the two sensors placed near ground level were installed in locations less accessible to the animals, close to the feeding equipment. All devices were fixed to solid structural elements using cable ties, ensuring stability and minimizing interference with the animals. The spatial distribution of the sensors within the barn is shown in Figure 2.9.

Some limitations related to sensor placement should be highlighted. Moreover, the proximity of some sensors to openings such as doors and windows may have influenced local measurements due to air exchange with the outdoor environment. Additionally, the non-uniform distribution of animals within the barn over time may lead to spatial variability in the measured parameters. Finally, the intrinsic limitations of the sensors, such as response time and measurement accuracy, should be considered when interpreting the collected data.



(a) Sensor installed in the animal area (purple marker in Figure 2.9)



(b) Sensor installed in the feeding alley (orange marker in Figure 2.9)



(c) Sensor installed near feeding equipment (grey marker in Figure 2.9)



(d) Sensor installed in the feed delivery alley (blue marker in Figure 2.9)

Figure 2.10: Examples of sensor installation inside the cattle barn.

The photos reported in Figure 2.10 show the actual positioning of the sensors within the

barn, highlighting the different installation heights and their distribution across the animal and feeding areas. In particular, the elevated positioning of most devices can be clearly observed, as well as the placement of ground-level sensors in protected locations. These examples also illustrate the practical constraints encountered during the installation phase, such as the need to avoid direct interaction with the animals and to ensure the stability of the devices. The use of elevated positions and fixed supports was therefore essential to guarantee reliable measurements over time. Furthermore, the images highlight some of the limitations discussed previously, such as the proximity of certain sensors to structural elements or openings, which may influence local measurements due to airflow patterns.

During the monitoring campaign, some data acquisition issues were identified. In particular, the Aranet sensor did not record data during the first week due to memory overwriting. Therefore, the available data for this device refer to the period 15th November to 12th December. In addition, one of the HOBO sensors (ID: 3135) provided unreliable CO₂ measurements after approximately two weeks of operation due to sensor drift, and these data were excluded from the analysis.

Chapter 3

Data processing and zone identification

Each sensor recorded data at a time resolution of 5 minutes. The monitoring period extended from 7 November to 12 December. The collected data were exported to Excel and initially analysed as a whole dataset. However, due to the large volume and variability of the data, the analysis was structured on multiple time scales. A weekly analysis was first performed to identify general trends and representative conditions. The aim of the analysis was to investigate the behaviour of the different barn zones by evaluating CO₂ concentration, air temperature, relative humidity and humidity ratio. In particular, the barn was analysed to identify potential zones characterized by similar thermal behaviour, for instance in terms of temperature trends over time and other environmental parameters. To better capture short-term dynamics and transient variations, a more detailed day-by-day analysis was also carried out, complementing the weekly assessment. Figure 3.1 shows an example of weekly temperature trends (15/11–22/11) at different sensor locations, highlighting the variability of the dataset. Since the observed values are very similar across the sensors, the identification of distinct zones within the barn becomes more challenging.

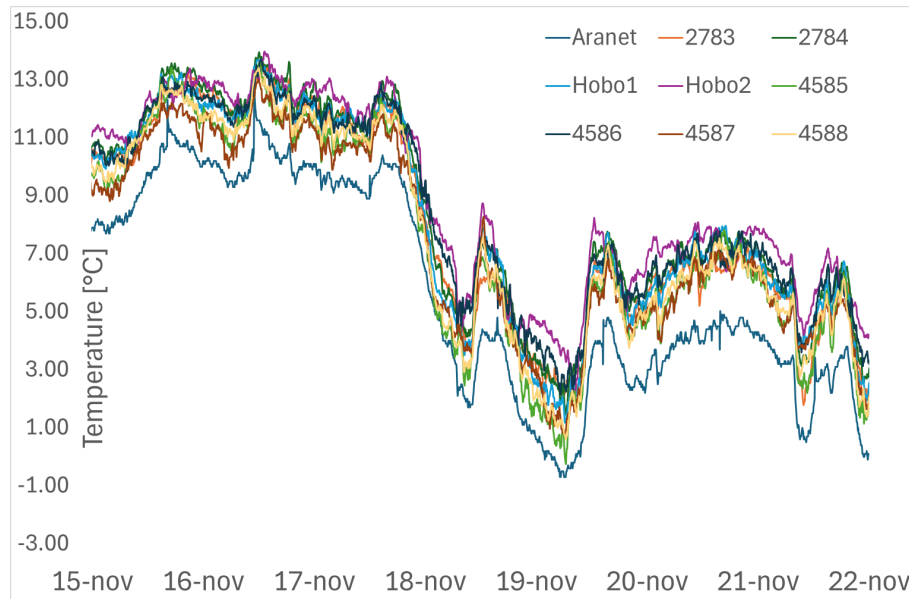


Figure 3.1: Example of weekly temperature trends measured by different sensors inside the barn from 15 November to 22 November

By contrast, when a daily time scale is considered, as shown in Figure 3.2, the differences in behaviour between the various zones of the barn become more evident.

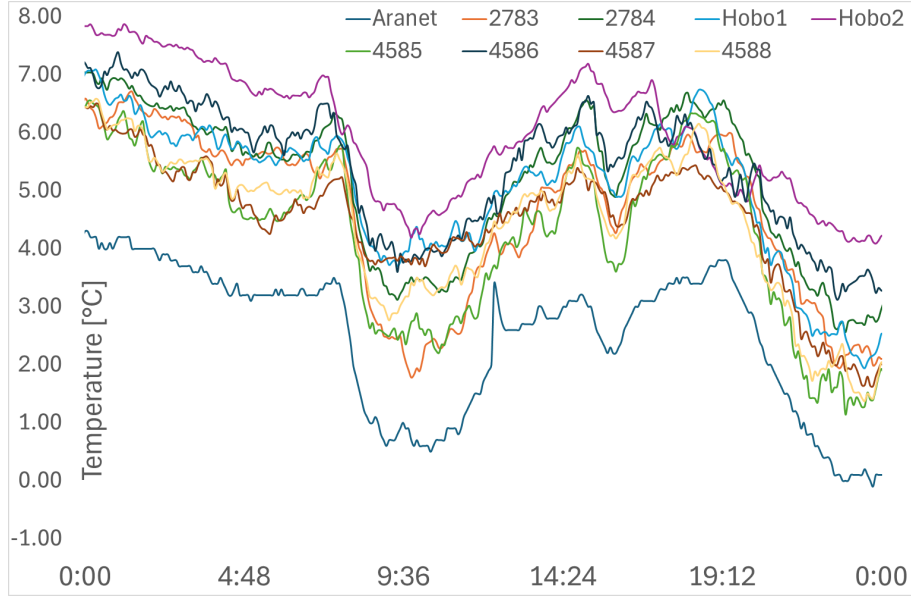


Figure 3.2: Example of daily temperature trends measured by different sensors inside the barn on November 21st

This higher temporal resolution enables a clearer identification of areas characterized by distinct environmental conditions. However, the interpretation of these patterns is not straightforward, as the behaviour of both the animals and the farmer within the barn is not directly monitored. For this reason, CO₂ concentration and air temperature trends were analysed on a day-by-day basis over the monitoring period, in order to infer the main activities occurring inside the barn. According to information provided by the farmer, the barn is opened two to three times per day for feeding operations and then promptly closed. These events are associated with the presence of the farmer and the activation of feeding machinery, which can influence the indoor environmental conditions. The Aranet sensor, positioned close to one of the main openings, was therefore used as a reference point to detect changes in the indoor environment related to these activities.

3.1 Zone identification

3.1.1 Temperature-based zone identification

By observing Figures 3.3–3.4, which report the weekly boxplots of indoor air temperature, it is possible to identify a clear separation among the sensors. In particular, the Aranet sensor consistently records significantly lower temperatures compared to all the other devices.

However, the grouping among the remaining sensors is less evident from a purely qualitative inspection of weekly data. For this reason, a more detailed analysis was carried out in order to identify possible groupings and define meaningful thermal zones within the barn.

An initial qualitative assessment was performed by analysing the temporal evolution of the measured temperatures, both on a weekly and daily basis. To support and formalize these

observations, a clustering analysis based on the mean absolute temperature difference between sensors was conducted, as shown in Figure 3.5. This approach allows the identification of groups of sensors characterized by similar thermal behaviour, leading to a clear subdivision into three main zones.

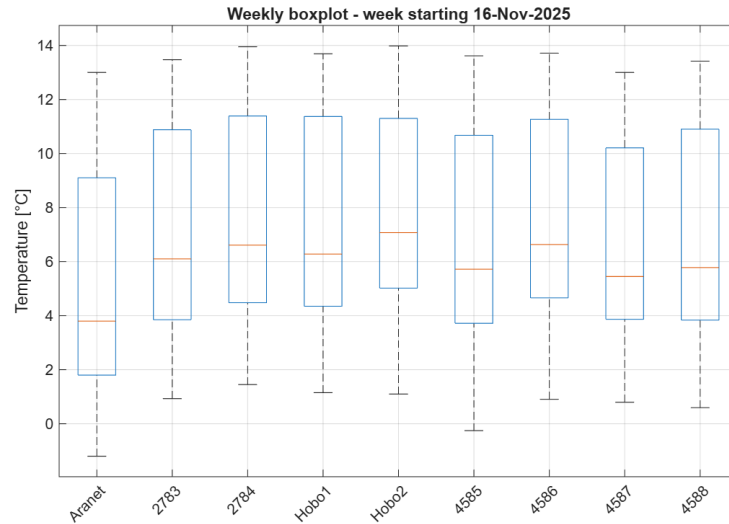


Figure 3.3: Weekly boxplot of indoor air temperature measured by different sensors inside the barn (week starting November 16th, 2025)

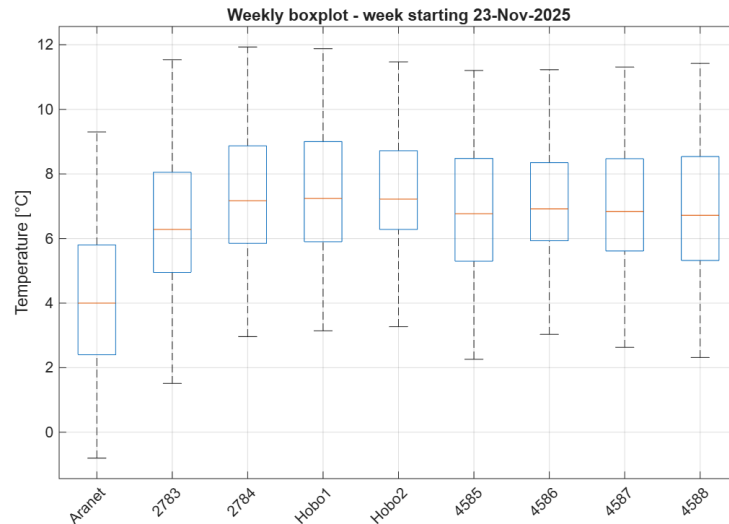


Figure 3.4: Weekly boxplot of indoor air temperature measured by different sensors inside the barn (week starting November 23rd, 2025)

In order to further interpret and validate the clustering results, the average daily temperature profiles of all sensors were analysed, as shown in Figure 3.6. The average daily profile is obtained by averaging the measured temperature at each hour of the day over the entire monitoring period. This method highlights the typical daily thermal behaviour of each sensor, reducing day-to-day variability and enabling a direct comparison between different locations.

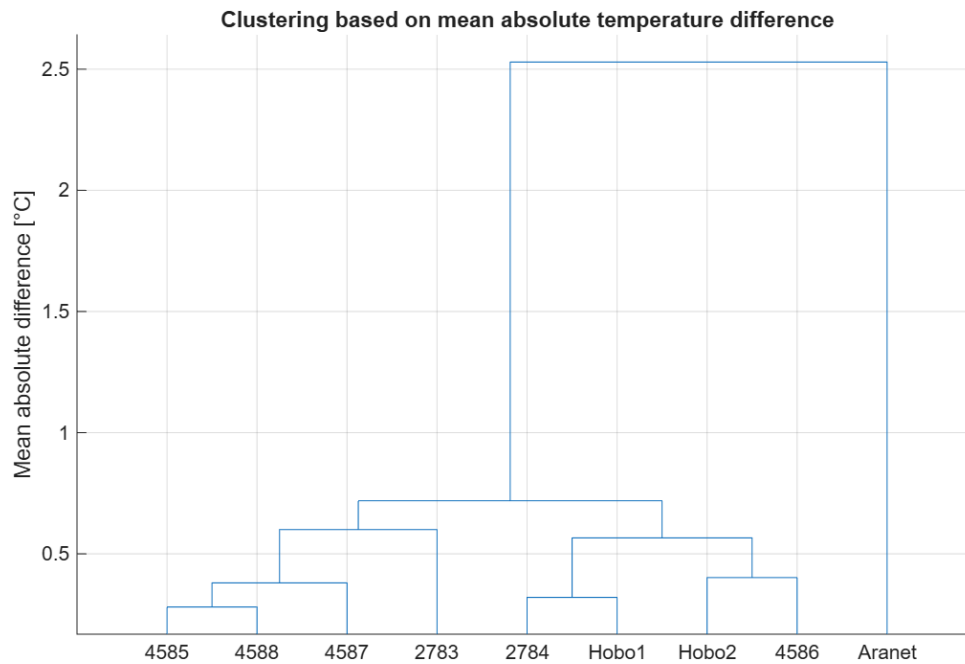


Figure 3.5: Thermal zone identification through hierarchical clustering based on mean absolute temperature differences

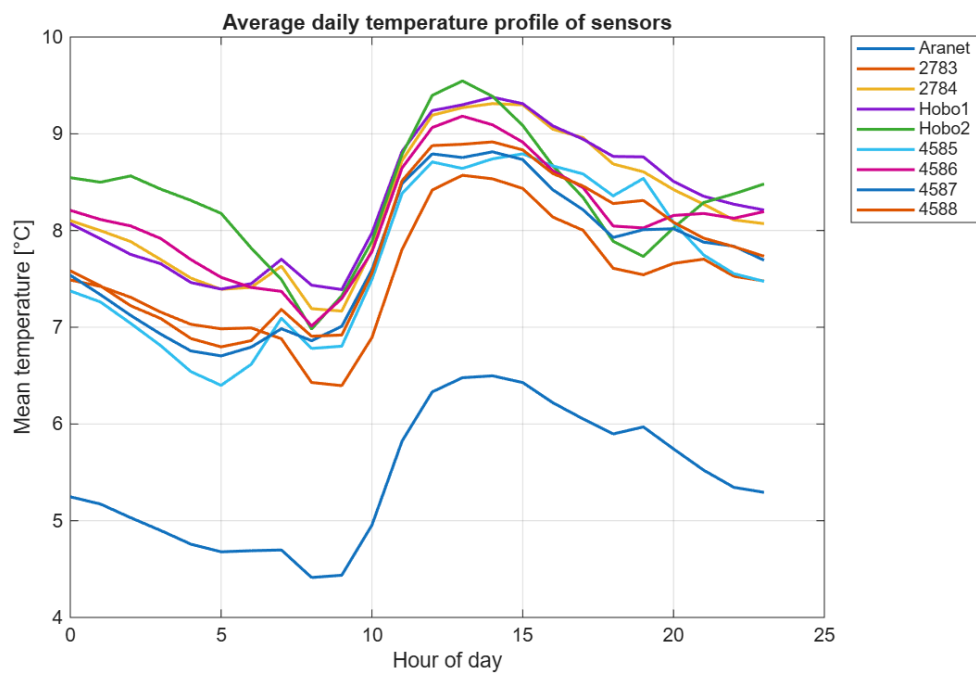


Figure 3.6: Average daily temperature profiles of the sensors used to support the clustering-based zone identification

The profiles show a common temporal pattern across all sensors, indicating that temperature variations are mainly driven by external boundary conditions. Nevertheless, significant differences in absolute temperature levels are observed. Sensors belonging to the same cluster exhibit very consistent behaviour, both in terms of trend and magnitude, confirming the robustness of the clustering procedure.

In particular, the Aranet sensor clearly deviates from the others, showing consistently lower temperatures. This behaviour suggests that it is located in a distinct thermal environment, likely influenced by its proximity to an opening.

To further support these observations, daily temperature trends were analysed. Figure 3.7 shows an example of the temperature evolution over a representative day.

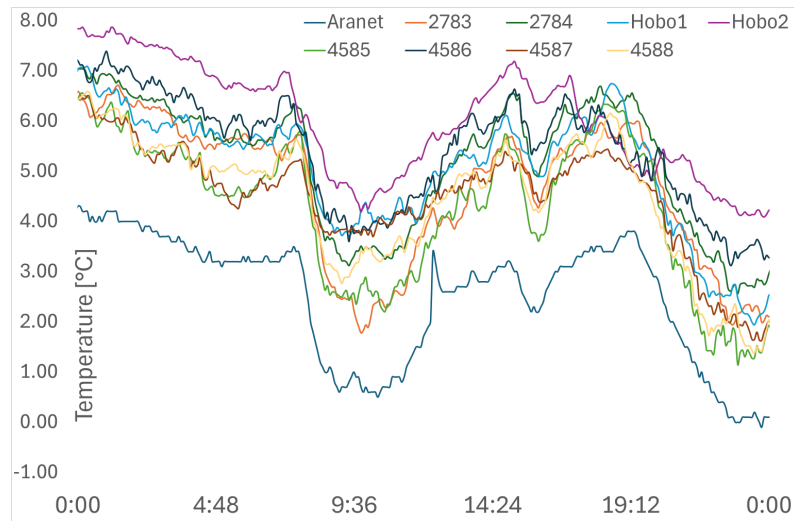


Figure 3.7: Example of daily temperature trends measured by different sensors inside the barn on November 21st

A common temporal behaviour can be observed across all sensors, while clear differences in temperature levels persist throughout the day. This confirms that the entire barn is influenced by the same external forcing, but local conditions lead to different thermal states.

These results indicate that, despite similar temporal dynamics, the spatial distribution of temperature within the barn leads to the formation of distinct thermal zones. Such differences are likely influenced by the position of the sensors, the proximity to openings, and the distribution of the animals, which act as internal heat sources. Overall, the consistency between the clustering results and the physical interpretation of the temperature profiles strengthens the identification of meaningful thermal zones within the barn.

The final zonization is summarized in Table 3.1. The identified zones are adopted in the

Table 3.1: Thermal zone classification of sensors based on hierarchical clustering analysis

Zone	Devices
Feed delivery alley	Aranet
Feeding alley	4585, 4587, 4588, 2783
Freestall	3134, 3135, 4586, 2784

following analyses to investigate the spatial variability of the environmental parameters within the barn.

3.1.2 CO₂-based zone identification

To further interpret the spatial variability observed in the temperature analysis, CO₂ concentration data were used to identify distinct zones within the barn. Since CO₂ is directly related to animal respiration and strongly influenced by ventilation conditions, it represents a suitable indicator for analysing both occupancy and air exchange patterns.

The analysis of CO₂ concentration shows a common temporal behaviour among the sensors, with simultaneous increases and decreases across the entire barn. This indicates that the indoor environment is influenced by global events affecting all zones. For instance, the variations observed on November 21st, shown in Figure 3.8, suggest that activities such as feeding operations or changes in ventilation conditions impact the barn as a whole. In particular, decreases in CO₂ concentration can be observed at approximately 7:00 and 15:00, likely associated with the opening of the barn, which enhances air exchange with the outdoor environment.

Despite the similar temporal trends, significant differences in the average CO₂ concentration levels are observed among the sensors. The Aranet sensor consistently records the lowest values, indicating a location closer to openings or in a more ventilated area. In contrast, the HOBO sensor with serial number 2784 shows the highest average concentrations throughout the monitoring period, suggesting a less ventilated zone characterized by higher accumulation of CO₂.

A group of sensors, including HOBO devices 2783, 3134, and 3135, exhibit comparable behaviour, with relatively small differences in CO₂ concentration (on the order of 100–200 ppm). This indicates that these sensors are located in areas characterized by similar ventilation efficiency and occupancy conditions.

Based on these observations, a zonization of the barn can be proposed according to CO₂ levels, which act as a proxy for both ventilation conditions and occupancy:

- **Zone 1:** Aranet sensor (low CO₂ concentration, associated with well-ventilated areas close to openings)
- **Zone 2:** HOBO sensor 2784 (high CO₂ concentration, associated with poorly ventilated areas and higher CO₂ accumulation)
- **Zone 3:** HOBO sensors 2783, 3134 and 3135 (intermediate CO₂ levels, representing areas with moderate ventilation and occupancy conditions)

However, it must be noted that the reliability of the CO₂ measurements is affected by sensor limitations. In particular, the HOBO 3135 sensor shows a clear measurement drift after approximately two weeks of operation, and its data were excluded from the analysis from November 30th onwards. A similar, although less pronounced, deviation is observed for HOBO 3134 in the final period, from December 7th until the end of the monitoring campaign, suggesting a potential reduction in measurement accuracy. These aspects were taken into account in the interpretation of the results, highlighting the importance of sensor validation in long-term monitoring campaigns. Despite these limitations, the CO₂-based zonization is consistent with the temperature-based classification, reinforcing the identification of distinct areas within the barn characterized

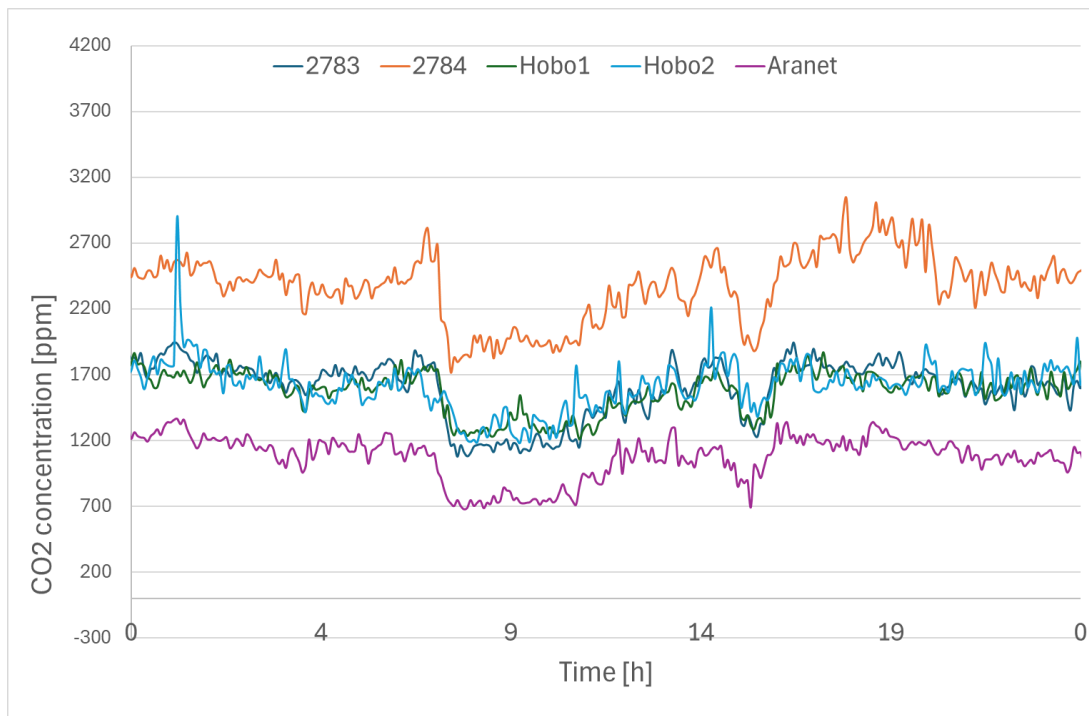


Figure 3.8: Example of daily CO₂ concentration trends measured by different sensors inside the barn on November 21st

by different environmental conditions. This consistency provides additional confidence in the definition of the zones adopted in the modelling approach described in the following sections.

3.2 Descriptive analysis of climatic data

In the following section, the environmental conditions within the barn are analysed based on the previously identified zones. The distributions of air temperature, relative humidity, humidity ratio, and CO₂ concentration are compared with the corresponding outdoor conditions. This comparison provides a clearer understanding of how the indoor environmental parameters varied over the seven-day period from 15 to 21 November. On the x-axis, each day is reported together with the corresponding indoor and outdoor datasets. For clarity, indoor boxplots are shown in blue, whereas outdoor boxplots are shown in orange.

3.2.1 Temperature

From Figures 3.9–3.11, it is evident that the feed delivery alley exhibits lower temperatures compared to the other zones, while the freestall generally shows slightly higher temperatures than the feeding alley. This difference can be attributed to animal presence, since cattle spend most of their time in the freestall area, contributing to higher internal heat production.

Outdoor temperature strongly influences indoor conditions, as shown by the decreasing trend observed during the analysed period. At the same time, the indoor distributions remain more stable than the outdoor ones, confirming the moderating effect of the barn structure and internal heat sources, which reduce the impact of external fluctuations.

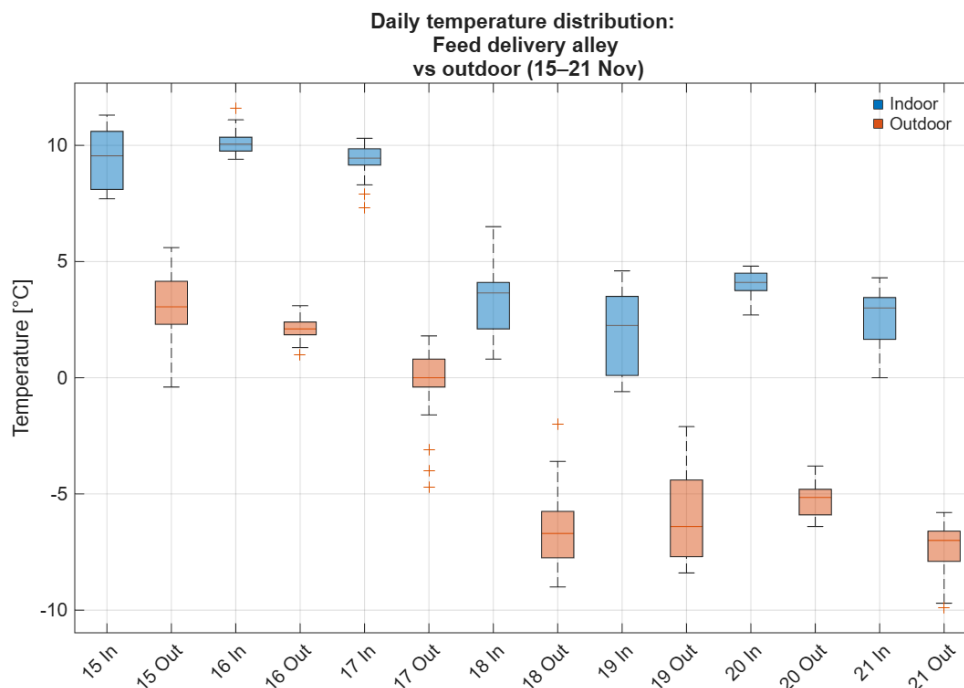


Figure 3.9: Daily distribution of indoor air temperature in the feed delivery alley, compared with outdoor conditions during the analysed period.

To provide a clearer comparison between the different zones, Figure 3.12 shows the temperature distributions for all areas over the analysed period and confirms the previously discussed predominance of higher temperatures in the freestall compared to the other zones.

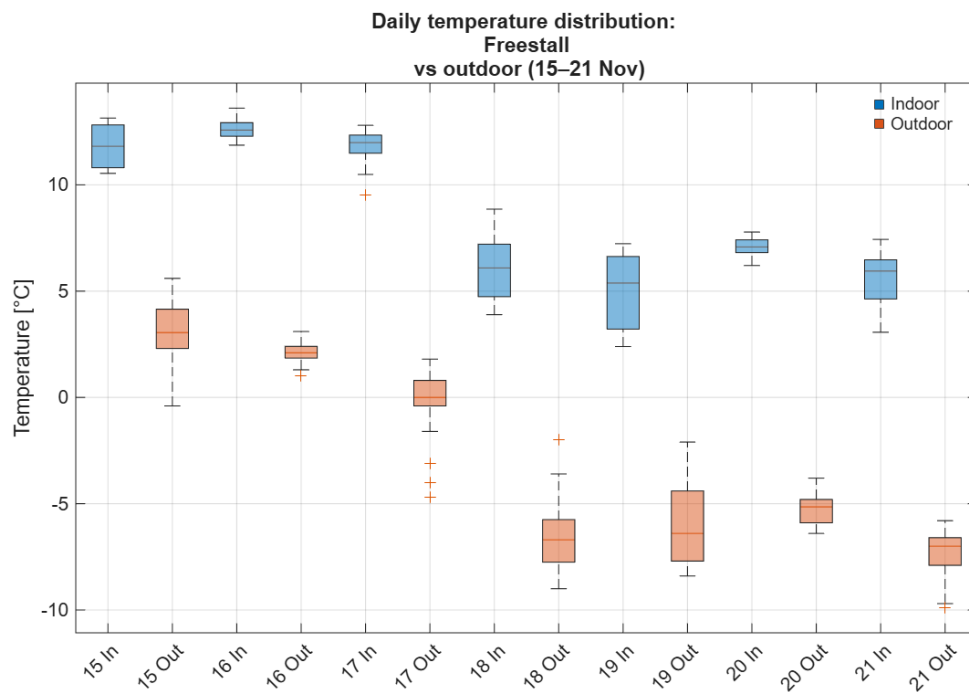


Figure 3.10: Daily distribution of indoor air temperature in the freestall, compared with outdoor conditions during the analysed period.

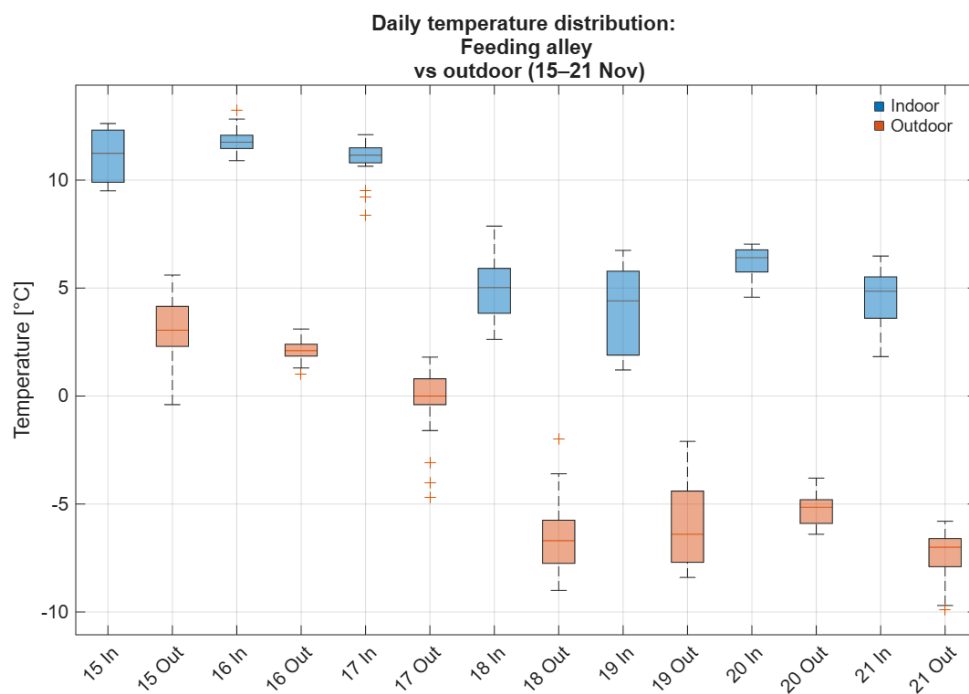


Figure 3.11: Daily distribution of indoor air temperature in the feeding alley, compared with outdoor conditions during the analysed period.

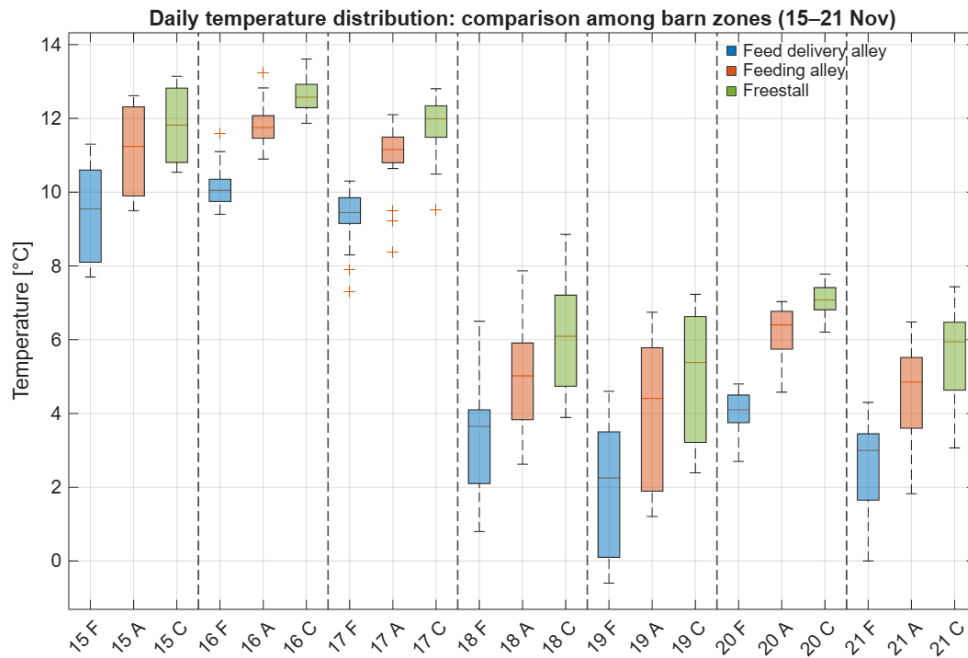


Figure 3.12: Daily distribution of indoor air temperature in the different barn zones (feed delivery alley, feeding alley and freestall) during the analysed period (15–21 November).

3.2.2 Relative humidity

Relative humidity (RH) (Figures 3.13–3.15) provides further insight into the moisture conditions within the barn. During most of the analysed period, outdoor RH values are close to saturation (approximately 100%), indicating very humid external conditions, potentially associated with fog, condensation phenomena, or precipitation events. However, a significant drop in outdoor RH can be observed on 19 November, highlighting the strong variability of external conditions. Indoor RH values remain consistently high but considerably more stable than the outdoor ones, generally ranging between 70% and 88%. This behaviour is due to the combined effect of high outdoor humidity and internal moisture production, mainly related to animal respiration, manure, and wet surfaces. At the same time, the reduced variability of indoor values suggests a buffering effect of the barn, which mitigates external fluctuations. Regarding the spatial distribution, the freestall (Figure 3.14) tends to exhibit slightly lower RH values compared to the other zones. This can be attributed to the higher presence of animals, which increases air temperature and consequently reduces relative humidity. In contrast, the feed delivery alley generally shows slightly higher RH values, likely due to reduced animal presence and different ventilation patterns, which favour moisture retention. The feeding alley exhibits intermediate behaviour between the two zones, reflecting both moderate animal presence and airflow conditions.

A direct comparison between the zones is shown in Figure 3.16. It can be observed that the feed delivery alley generally exhibits higher RH values compared to the other zones. During the first three days (15–17 November), the feeding alley shows the lowest values, while the freestall tends to have higher RH.

On 18 November, a change in the relative behaviour of the zones can be observed, with the feeding alley exhibiting higher RH values compared to both the feed delivery alley and

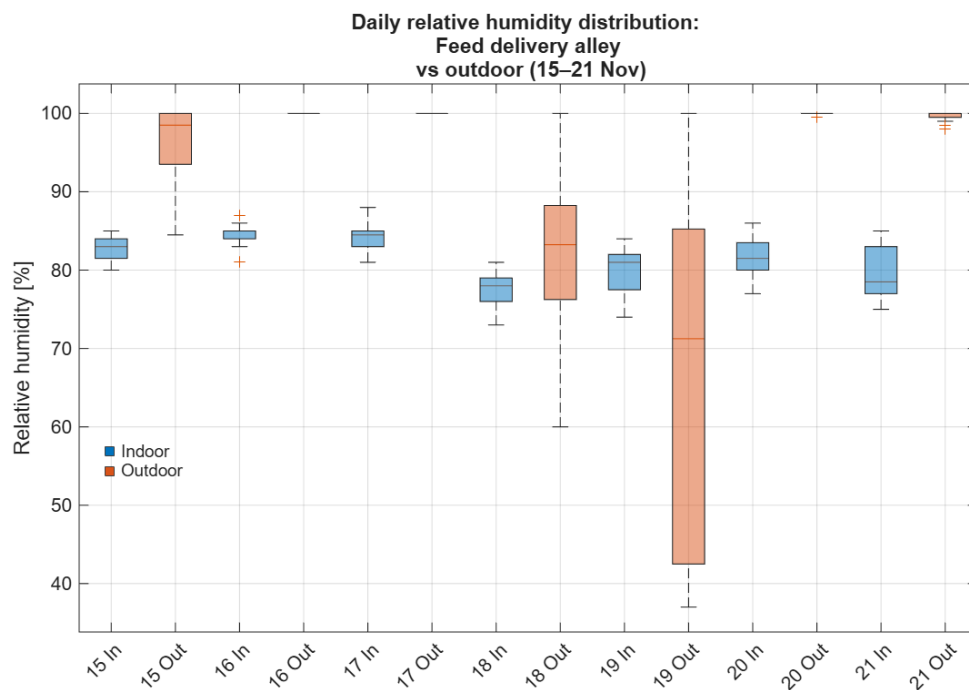


Figure 3.13: Daily distribution of indoor relative humidity in the feed delivery alley, compared with outdoor conditions during the analysed period.

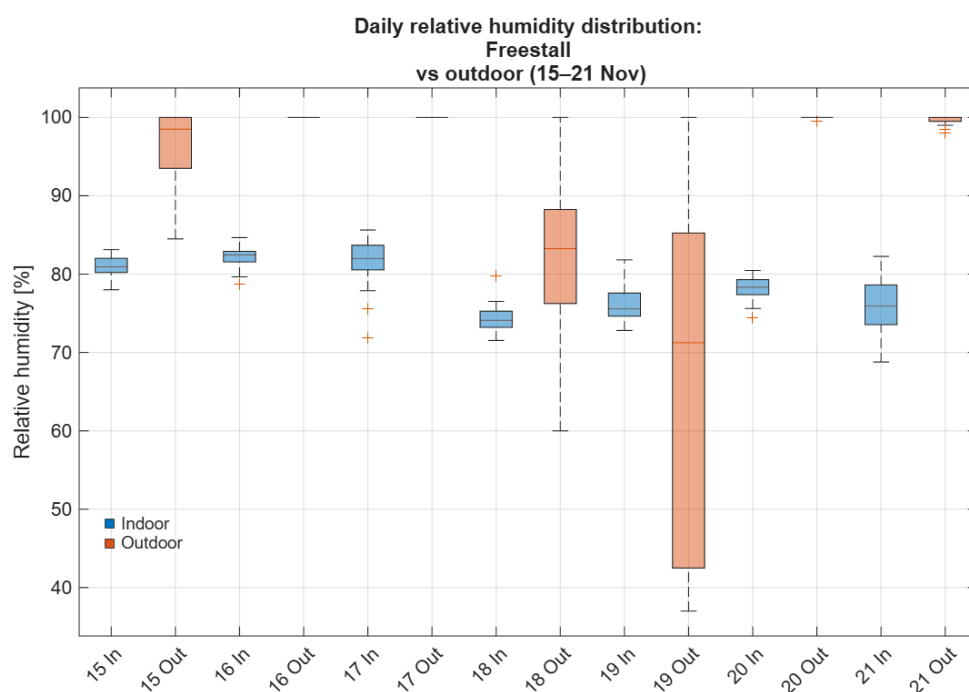


Figure 3.14: Daily distribution of indoor relative humidity in the freestall, compared with outdoor conditions during the analysed period.

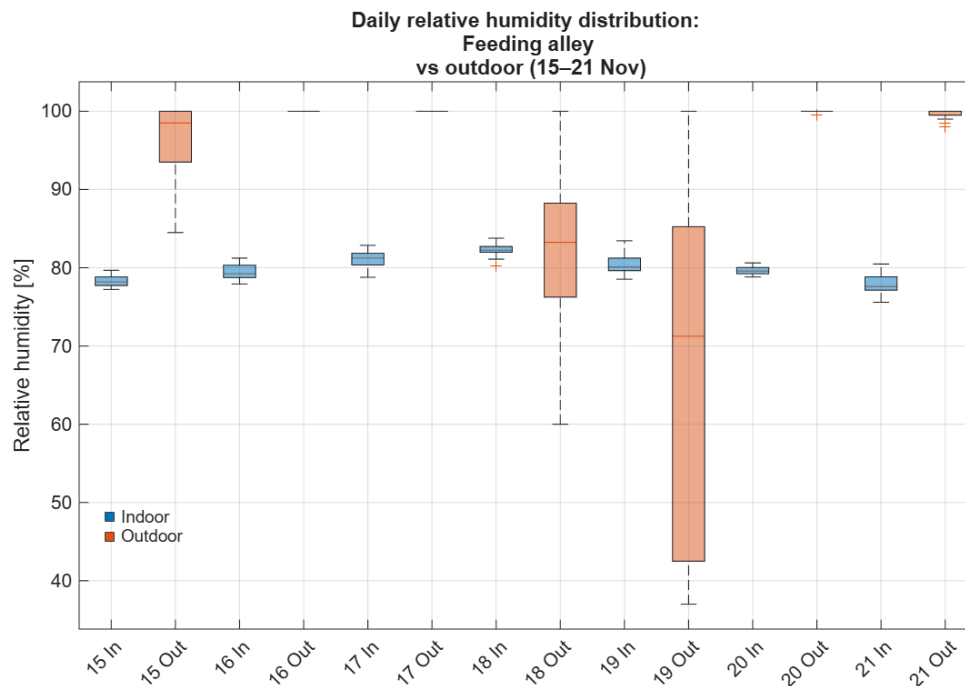


Figure 3.15: Daily distribution of indoor relative humidity in the feeding alley, compared with outdoor conditions during the analysed period.

the freestall. This variation can be attributed to changes in external conditions and ventilation patterns, as well as possible differences in internal heat gains, which affect the balance between temperature and moisture content.

During the last three days (19–21 November), the feed delivery alley again shows the highest RH values, while the freestall tends to exhibit the lowest values. This confirms that, despite the presence of higher moisture production in the freestall, the higher air temperatures in this zone lead to a reduction in relative humidity.

Overall, the results highlight how both external conditions and internal processes contribute to maintaining high humidity levels within the barn. Despite the strong variability observed outdoors, the indoor environment remains relatively stable, with spatial differences mainly driven by animal distribution, thermal conditions, and local airflow patterns. This confirms that ventilation effectiveness plays a key role in controlling humidity, particularly in areas with higher animal density.

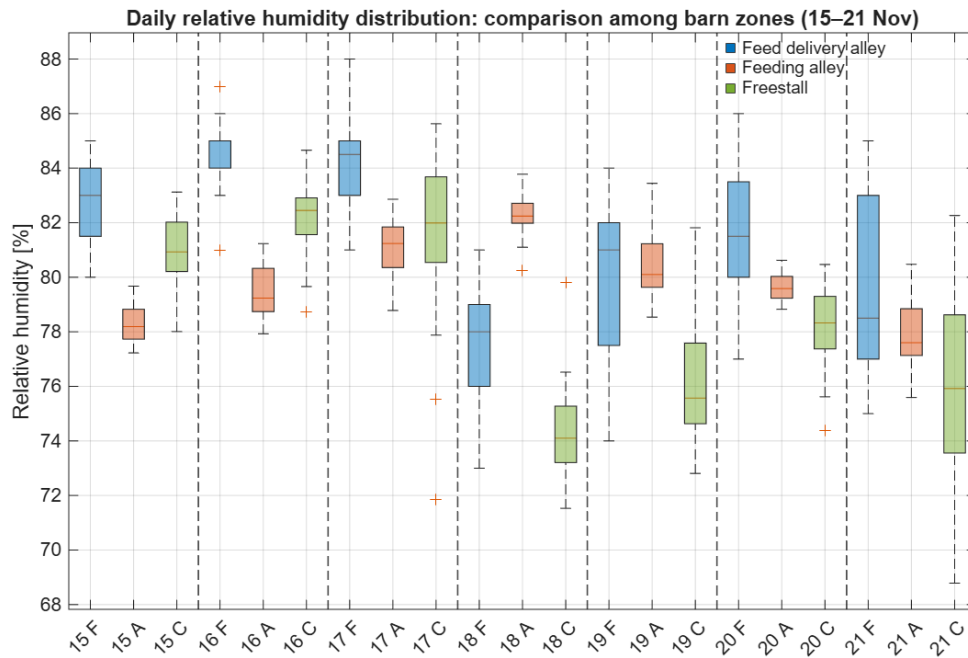


Figure 3.16: Daily distribution of indoor relative humidity in the different barn zones (feed delivery alley, feeding alley and freestall) during the analysed period (15–21 November).

3.2.3 Humidity ratio

Humidity ratio provides a more direct description of the actual moisture content of the air within the barn. In contrast to relative humidity, which is influenced by both temperature and vapour content, the humidity ratio directly reflects the amount of water vapour present in the air.

During the analysed period, the outdoor humidity ratio shows significant variability, whereas indoor values remain consistently higher, indicating a greater accumulation of moisture within the barn. This difference is mainly due to internal moisture sources, particularly animal respiration and evaporation from manure and wet surfaces associated with animal activity. Indoor humidity ratio generally ranges between approximately 4 and 9 g/kg, whereas outdoor values are lower. This confirms a clear moisture accumulation within the barn environment. Among the different zones, the freestall exhibits the highest humidity ratio values, as animals spend most of their time in this area, leading to increased moisture production. In contrast, the feed delivery alley shows the lowest values, due to the limited presence of animals and consequently reduced internal moisture generation, while the feeding alley shows intermediate behaviour.

Overall, these results highlight the strong influence of animal presence on indoor moisture conditions and the important role of ventilation in controlling vapour accumulation (Figures 3.17–3.19).

A direct comparison between the zones is shown in Figure 3.20. The same general trend can be observed throughout most of the analysed week: the freestall exhibits the highest humidity ratio values, the feeding alley intermediate values, and the feed delivery alley the lowest ones. This confirms that the moisture content of the air is strongly influenced by animal distribution inside the barn.

On 18 and 19 November, both the freestall and the feeding alley show lower humidity ratio values compared to the first part of the week, and their distributions become more similar.

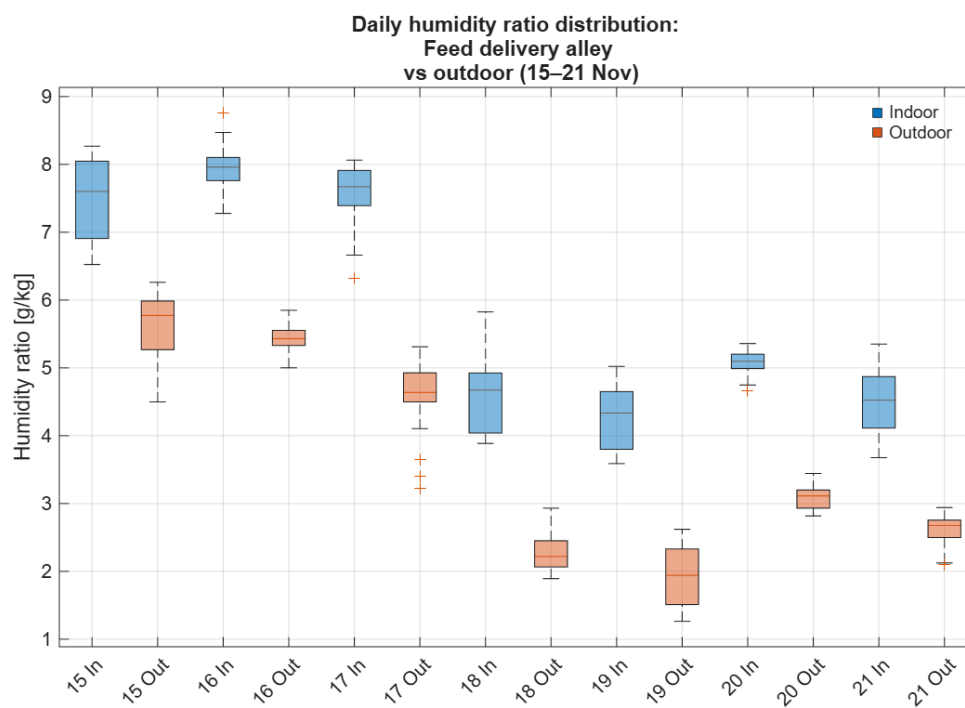


Figure 3.17: Daily distribution of indoor humidity ratio in the feed delivery alley, compared with outdoor conditions during the analysed period.

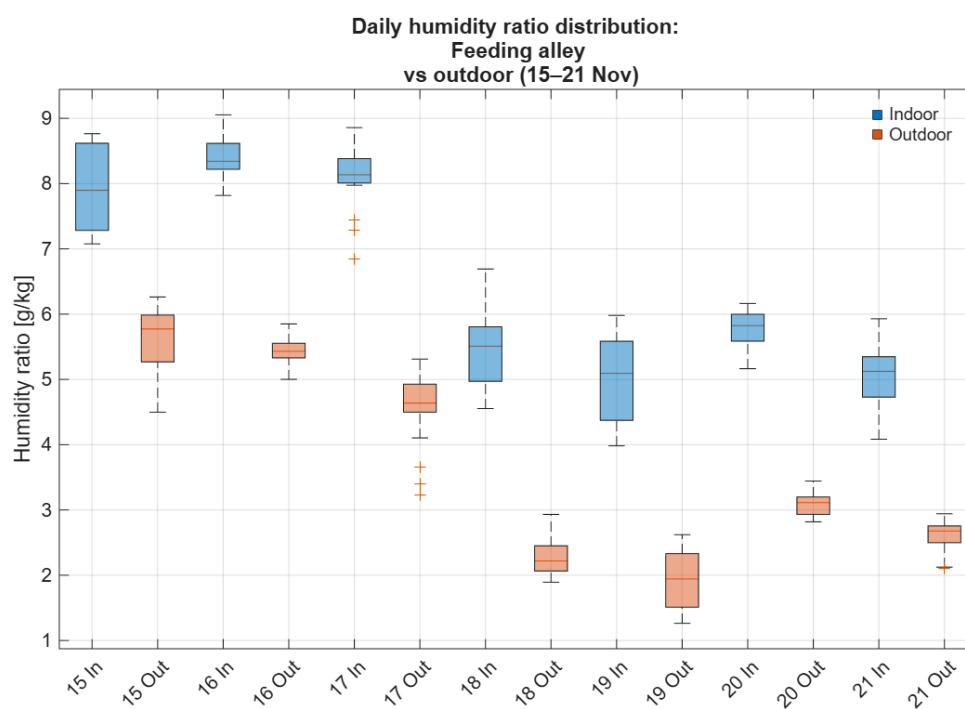


Figure 3.18: Daily distribution of indoor humidity ratio in the feeding alley, compared with outdoor conditions during the analysed period.

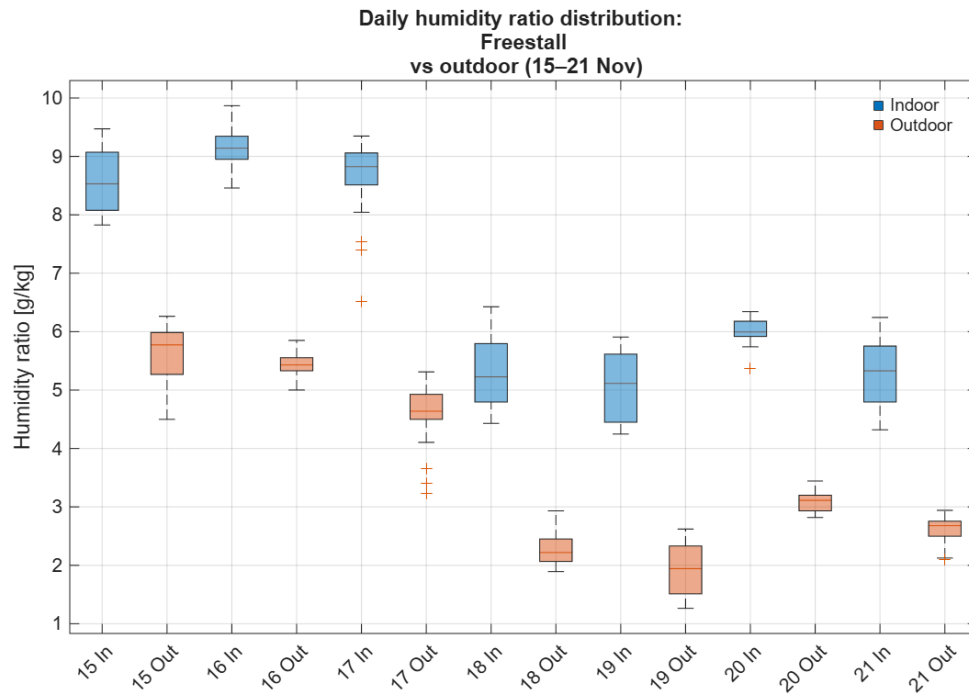


Figure 3.19: Daily distribution of indoor humidity ratio in the freestall, compared with outdoor conditions during the analysed period.

This behaviour is likely related to the lower outdoor moisture content observed during the same period, combined with changes in ventilation conditions that may have enhanced moisture removal from the indoor environment. The reduction in air temperature alone would not explain a lower humidity ratio, since humidity ratio depends on the actual vapour content rather than directly on temperature.

During the last two days, the same spatial trend observed at the beginning of the week is restored, although all zones show lower values compared to the initial days. This suggests that the relative differences between the barn zones remain consistent, while the absolute moisture levels vary depending on the external boundary conditions and the resulting ventilation behaviour.

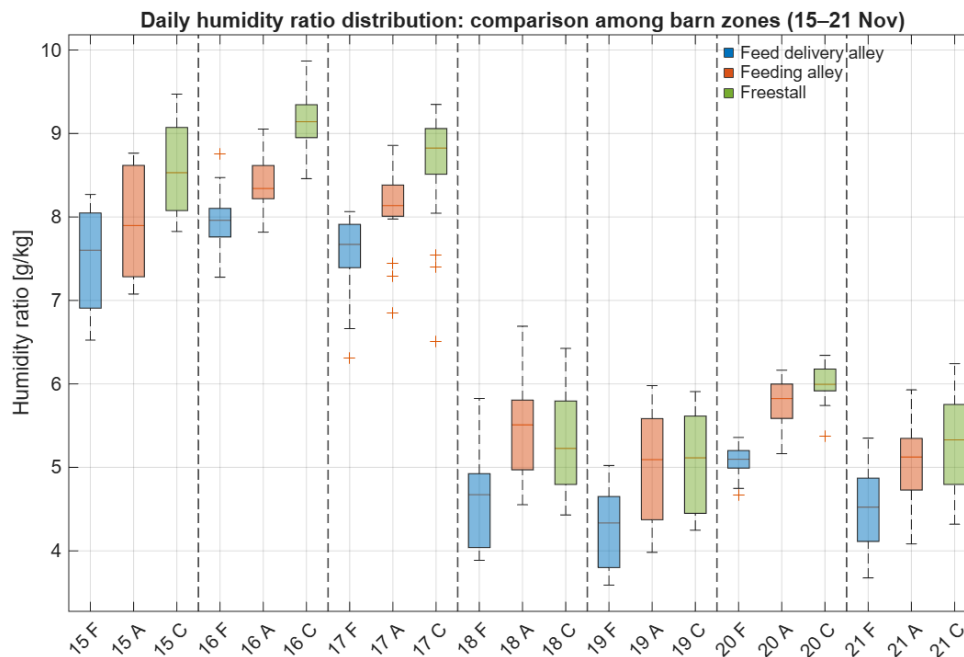


Figure 3.20: Daily distribution of indoor humidity ratio in the different barn zones (feed delivery alley, feeding alley and freestall) during the analysed period (15–21 November).

3.2.4 CO₂ concentration

The last comparison concerns CO₂ concentration. Outdoor CO₂ levels are typically around 400 ppm, which represents the current atmospheric baseline. In occupied indoor environments, CO₂ concentration generally increases due to respiration, but with adequate ventilation it usually remains within acceptable limits.

In livestock buildings, CO₂ concentrations are significantly higher, typically exceeding 800 ppm due to animal respiration. Among the analysed zones, the freestall exhibits the highest values, generally ranging between approximately 1500 and 2300 ppm. This is consistent with the higher animal density and the longer residence time of cattle in this area.

The feed delivery alley and the feeding alley show lower concentrations than the freestall, but still clearly above typical outdoor values. In general, the feed delivery alley exhibits values comparable to, or slightly lower than, those of the feeding alley during the first part of the analysed period, whereas in the last two days a more evident separation between the two zones can be observed.

Figure 3.21 provides a direct comparison among the three zones and clearly highlights the predominance of higher CO₂ concentrations in the freestall. This behaviour can be directly related to the more constant presence of the animals in this zone during the day.

A particular behaviour can be observed on 18 November, when the feed delivery alley shows a wider distribution and higher values compared to its typical pattern. This may be associated with a prolonged use of machinery inside the barn, or more generally with temporary changes in occupancy and airflow conditions.

Overall, the results clearly indicate that animal respiration is the primary source of CO₂ within the barn, while ventilation plays a key role in controlling its accumulation. The observed variability in CO₂ levels reflects the combined influence of animal distribution, possible farming

activities, and local airflow patterns, with higher concentrations associated with reduced air exchange rates.

It would be relevant to further investigate whether the observed CO₂ concentrations fall within acceptable limits for animal welfare, as elevated levels may indicate insufficient ventilation.

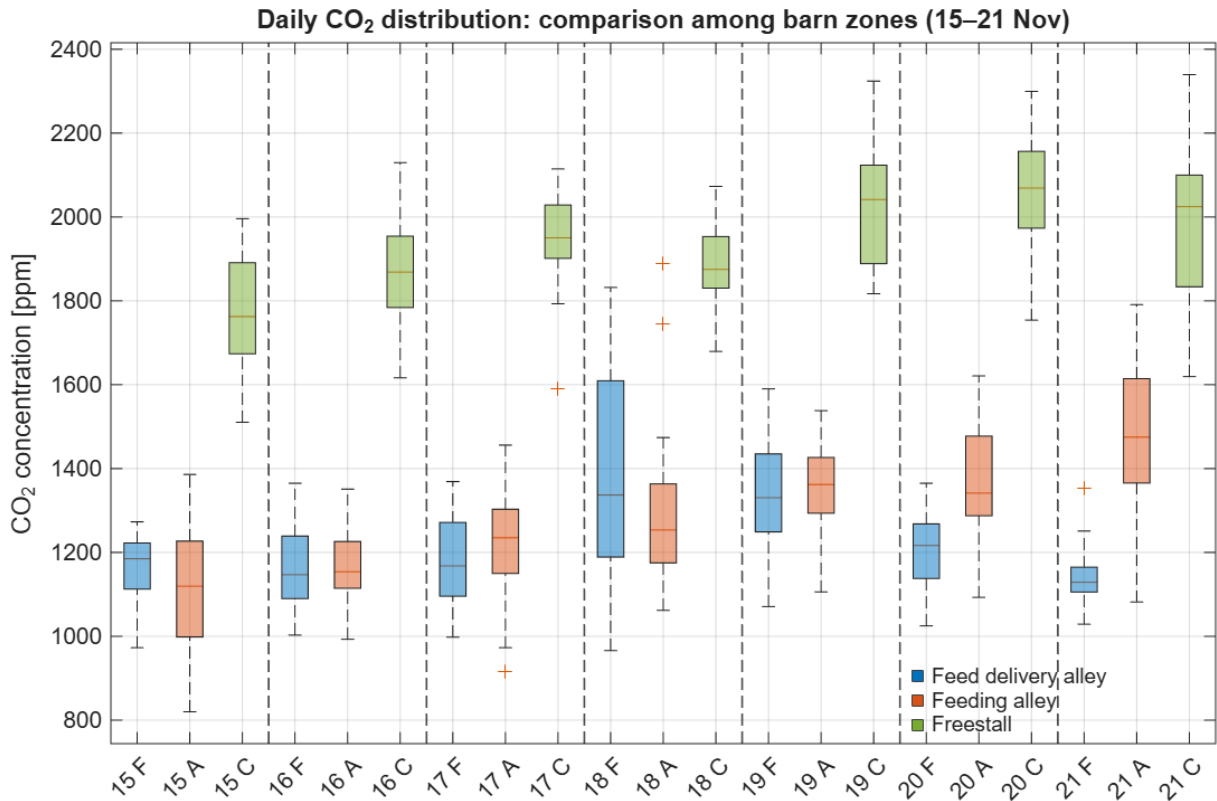


Figure 3.21: Daily distribution of CO₂ concentration in the different barn zones (feed delivery alley, feeding alley and freestall) during the analysed period (15–21 November).

- **Zone 3 – Freestall (resting area):** area mainly occupied by animals, showing relatively stable but slightly higher CO₂ concentrations and temperatures due to the continuous presence of animals, which spend most of their time resting in this zone.
- **Zone 4 – Roof zone:** upper part of the barn, included to account for thermal stratification and its influence on heat transfer and ventilation dynamics. As no sensors were installed in this area, it was introduced to represent the effect of the continuous roof opening (*ridge vent*) and to account for buoyancy-driven airflow (stack effect).

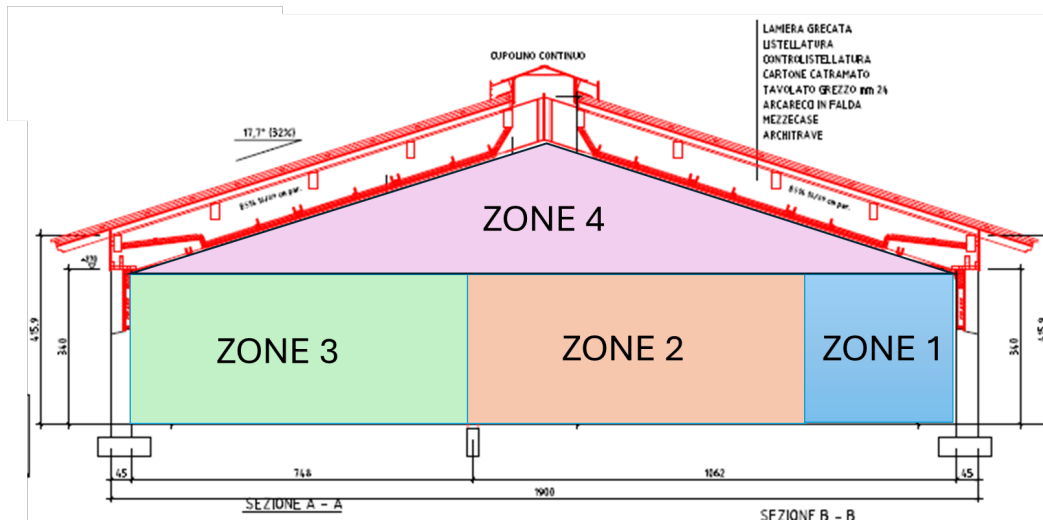


Figure 4.2: Zonization of the barn in vertical section, including the roof zone

This zonization represents a simplified but physically meaningful description of the barn, and it is used as the basis for the definition of thermal zones in the subsequent simulation model.

4.2 Modelling approach

Once the zonization phase was completed, the development of the simulation models was carried out. Two main software tools were used: TRNSYS (TRaNsient SYstems Simulation) [49] and CONTAM [50].

TRNSYS is a flexible, graphically based simulation environment widely used to model the dynamic behaviour of transient systems. It is primarily applied to thermal energy systems, including buildings, HVAC systems, and renewable energy technologies. The simulation environment is based on modular components, referred to as “Types”, which represent individual system elements. Each Type processes input variables and produces output variables, interacting with other components within the simulation framework.

CONTAM, developed by the National Institute of Standards and Technology (NIST), is a multizone indoor air quality (IAQ) and ventilation analysis tool. It is used to simulate airflow and contaminant transport within buildings.

The coupling between the thermal model and the airflow model was implemented in TRN-SYS Simulation Studio, where the TRNSYS building model–TRNBuild (Type 56) was linked

with the CONTAM model (Type 97). This approach enabled annual simulations of the case study to capture the thermal dynamics of the barn, accounting for natural ventilation patterns. In the following sections, the modelling approach is described in detail, starting from the TRN-SYS model and then introducing the CONTAM model.

4.2.1 TRNBuild – Type 56

The first step, after defining the general information of the project, is to set the orientation of the barn and select the correct hemisphere. This is necessary to ensure an accurate representation of solar radiation, wind exposure and other outdoor boundary conditions within the simulation environment.

Then it was possible to define the construction layers, which are subsequently used to model the building envelope of the barn. Since the properties required to define each layer are thermal conductivity [$\text{kJ}/(\text{h m K})$], specific heat capacity [$\text{kJ}/(\text{kg K})$], and density [kg/m^3], while the available data included only thickness [cm], thermal conductivity λ [$\text{W}/(\text{m K})$], and thermal resistance R [$\text{m}^2\text{K}/\text{W}$] (Tables 2.1-2.2), it was necessary to retrieve additional thermophysical properties from literature sources. This approach introduces a potential source of uncertainty; however, the adopted values are consistent with typical ranges reported in the literature and are considered acceptable for the purposes of the simulation.

Table 4.1: Thermophysical properties of materials used in the model

Material	Conductivity [$\text{kJ}/(\text{h m K})$]	Specific heat capacity [$\text{kJ}/(\text{kg K})$]	Density [kg/m^3]
Profiled wood (tongue and groove)	0.468	1.600	450
Vapour barrier (sd = 0.10 m)	0.792	1.800	950
Glass wool WLG040	0.144	1.030	40
Spruce wood (8.3%)	0.468	1.600	450
Profiled wood (spruce/fir)	0.504	1.600	440
Roofing membrane (sd = 0.10 m)	1.800	1.900	920
Rear ventilated air layer (94%)	1.127	1.005	1.2
Trapezoidal metal sheet	36.000	0.480	7850
Plasterboard panel	0.900	1.000	750
OSB/3 panel	0.468	1.700	620
Polyethylene sheet (PE)	1.440	2.000	920
Mineral wool 035	0.126	1.000	90
Solid concrete	5.040	0.880	2200
Vulcanized rubber	1.080	1.700	1200
Straw	0.180	1.500	80
Polyurethane	0.0864	1.400	35
Still air layer 2	10.894	1.005	1.2
P800	0.648	0.100	830

Note on units: Thermal conductivity is expressed in [$\text{kJ}/(\text{h m K})$] throughout this work, in accordance with the internal unit system of TRNSYS. Although the International System of Units (SI) recommends the use of [$\text{W}/(\text{m K})$], this choice was adopted to maintain consistency

with the simulation outputs, ensuring direct comparability of results and avoiding potential errors associated with unit conversion.

Other parameters expressed in terms of thermal power or heat transfer are also reported in kJ/h for the same reason, despite the SI convention of using Watts.

An air layer, not reported in Table 4.1, was introduced as a massless layer with an assigned thermal resistance of 0.06 [(h m² K)/kJ], in order to ensure numerical stability and convergence of the simulation.

Subsequently, the defined layers were combined to construct the building elements (walls, floors, ceilings and roof), according to the stratigraphies reported in Tables 2.2 and 2.1 and described in Section section 2.1.

The window components, assumed to be identical, were modelled using typical properties derived from the default values provided by the software. Due to the lack of detailed information, these parameters were adopted as representative of double-glazed window systems commonly used in agricultural buildings. The assumed properties are summarized in Table 4.2.

Table 4.2: Assumed thermal and optical properties of the windows

Parameter	Value	Unit
Glazing type	Double glazing	–
Thermal transmittance (U-value)	1.1	W/m ² K
Solar heat gain coefficient (g-value)	0.62	–
Frame fraction	0.15	–
Frame conductance	8.17	kJ/h·m ² K
Internal convective coefficient	11	kJ/h·m ² K
External convective coefficient	64	kJ/h·m ² K

At this stage, after defining the building envelope, the internal loads were introduced, which in this case correspond to the presence of dairy cattle inside the barn.

The internal heat gains were defined based on the sensible and latent heat production of the animals. The heat emission of each cow was estimated as a function of its body mass and metabolic activity, according to the correlation proposed in Table 4.4.

In addition, a schedule was assigned to describe the temporal distribution of the animals within the different zones of the barn. This schedule represents the occupancy profile of the cattle and was defined based on the typical daily behaviour provided by the farmer, considering that the animals spend most of the time in the freestall area. These internal loads play a key role

Table 4.3: Daily schedule of internal heat gains associated with animal presence in the feeding alley and freestall areas

Time interval	Schedule value [-]	Description
00:00 – 07:00	0.00	No animal activity
07:00 – 19:00	0.20	Animal presence and feeding activity
19:00 – 24:00	0.00	No animal activity

in the thermal balance of the system, significantly influencing both the indoor temperature and humidity conditions.

The first input concerns the activity schedule of the animals. Based on information provided by the farmer, the cattle spend most of their time in the freestalls. Therefore, the schedule was defined considering two main periods, namely daytime and nighttime, assigning higher occupancy to the resting area. The adopted schedule is shown in Table 4.3 and Figure 4.3.

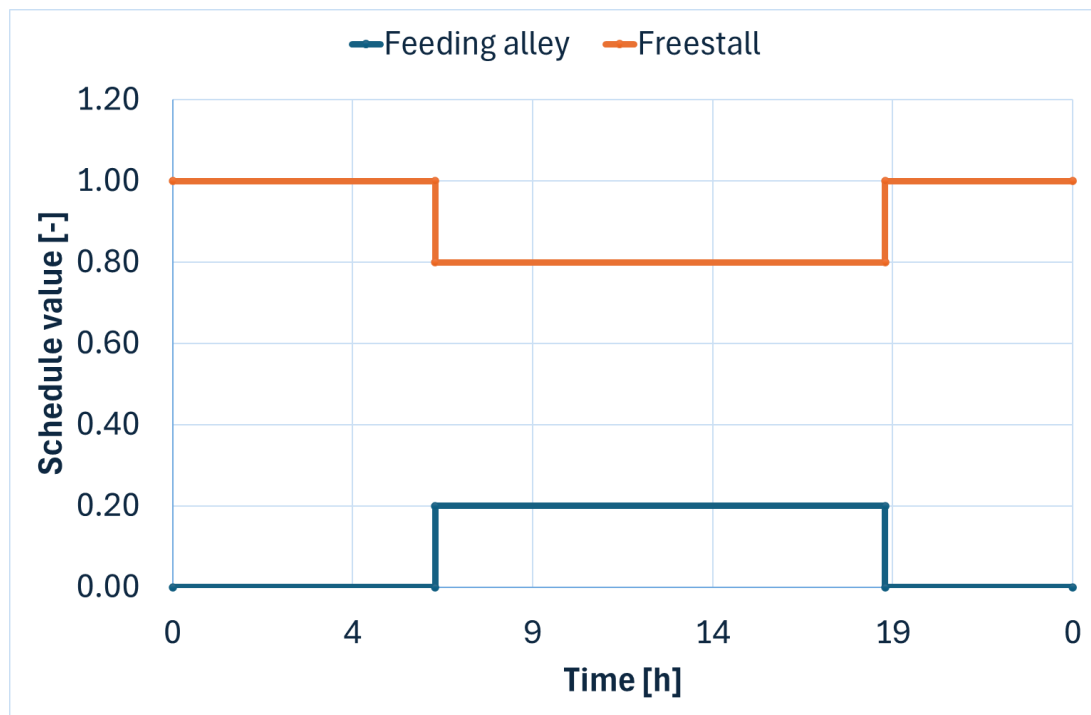


Figure 4.3: Daily schedule of animal-related internal heat gains in the feeding alley and freestall areas

After defining the internal heat gains associated with the presence of cattle, the next step consisted in modelling the air exchange within the barn in order to account for the effects of natural ventilation. Infiltration was therefore introduced to represent the air exchange between the outdoor environment and the indoor zones. This process was modelled in terms of air changes per hour [1/h], which quantify the rate at which indoor air is replaced by outdoor air. To accurately describe the airflow distribution within the building, a ventilation network was implemented in CONTAM. The barn was discretised into interconnected zones, and airflow paths were defined between zones and between indoor and outdoor environments. Different types of connections were considered, including leakage elements to represent infiltration through openings (e.g., windows and doors), and large openings modelled as two-way flow elements. This approach allows capturing the interaction between natural ventilation and internal heat gains, which together govern the thermal conditions inside the barn.

The heat gains due to the presence of cattle were evaluated using the correlations described in Chapter 1.1.2, as reported in Equation 1.1. Assuming an average animal weight of 600 kg, the resulting radiative, convective, and latent heat gains, as well as the associated moisture production, are reported in Table 4.4.

Table 4.4: Cattle's heat gain and moisture production

Radiative [kJ/h]	Convective [kJ/h]	Latent [kJ/h]	Abs. Humidity [kg/h]
973.0	796.6	3432.3	1.4

Within each zone, all surfaces (walls, floors, ceilings, and roof) are defined by specifying their construction type, surface area, orientation, and boundary condition (external, internal, or adjacent). For instance, the north-oriented wall includes eight windows, each characterized by its area, U-value, g-value, and boundary condition. In the case of adjacent surfaces, the corresponding connected zone must be specified, while for surfaces exposed to the external environment, the associated infiltration paths must be defined. For surfaces in contact with the ground, the ground temperature was imposed as a boundary condition, using the input provided by Type 77 in TRNSYS Simulation Studio. For surfaces adjacent to the technical area (highlighted in yellow in Figure 2.2), an internal boundary condition was assumed, using an air layer as construction type.

Finally, the coupling between zones was defined. Each zone is connected to adjacent zones through airflow paths. For instance, the feed delivery alley is connected to both the roof zone and the feed distribution area. For each zone, these connections must be explicitly defined in order to correctly represent inter-zone air exchange within the simulation model.

4.2.2 Airflow modelling and assumptions in CONTAM

The second software used in this study is CONTAM, which is employed to define a ventilation network composed of air nodes connected by airflow paths. This network allows the calculation of airflow rates between zones, including exchanges with the outdoor environment, based on internal conditions, external weather conditions, and the characteristics of openings.

Since the barn is naturally ventilated, with no mechanical ventilation systems, the indoor environmental conditions are primarily driven by external climatic conditions. As previously discussed, the simulation of natural ventilation presents several limitations, particularly in accurately predicting airflow patterns and infiltration rates. In this case, the indoor conditions are mainly influenced by air infiltration through openings such as windows and doors. Air exchange is ensured by the stack effect, generated by the continuous roof opening, which promotes vertical airflow and natural ventilation within the building. This section describes the geometrical and airflow model of the barn as implemented in CONTAM, including the definition of zones and airflow paths.

The same zoning configuration adopted for the thermal model was also used in CONTAM.

Thus, the first step consists in defining each zone together with its main geometrical properties, namely volume and floor area.

Subsequently, the airflow interactions between zones and between indoor and outdoor environments are defined. Two different modelling approaches are adopted depending on the type of opening. Infiltration through closed components, such as windows, doors and overhead doors, is modelled using a leakage area approach, expressed in $[\text{cm}^2/\text{m}]$, based on a power law formulation. Conversely, large openings without obstructions, including direct connections between zones and openings such as windows and doors when open, are modelled using two-way flow elements. For the connections between the ground floor and the upper zone (roof), as well as

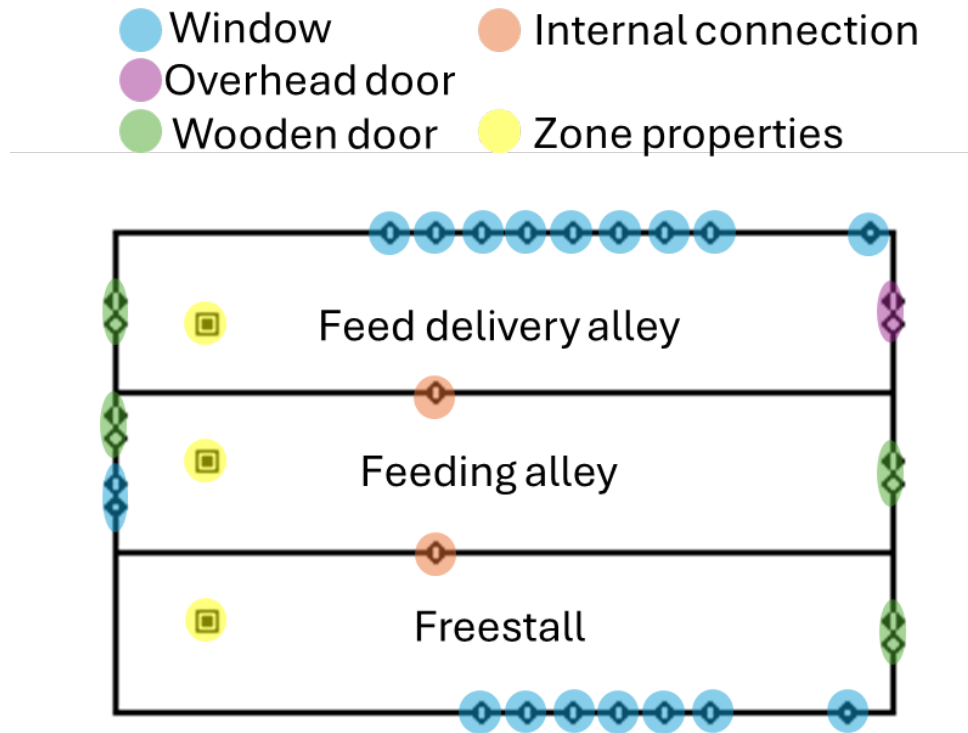


Figure 4.4: Schematic representation of the barn model implemented in CONTAM, showing the subdivision into thermal zones and the airflow paths between zones and with the outdoor environment.

between the roof and the outdoor environment, one-way flow elements are adopted. In these cases, the airflow is modelled through an equivalent orifice, whose area corresponds to the floor area of the connected zone.

The main parameters adopted in the model are summarized in Table 4.5.

Table 4.5: Airflow paths modelled as large openings (two-way flow elements)

Connection	Height [m]	Width [m]	Midpoint [m]	C_d [-]	Flow coeff.
Feed delivery – Feeding	3.4	29.8	0.756	0.78	55.88
Feeding – Freestall	3.4	39.8	0.756	0.78	74.63
Windows	0.8	3.6	0.178	0.78	1.59
Basculante	3.5	3.2	0.778	0.78	6.18
Wooden doors	2.5	2.5	0.556	0.78	3.45

The values assigned to the leakage parameters and the boundary conditions are discussed in detail in the following section, where the model setup is further refined and analyzed.

4.2.3 TRNSYS–CONTAM coupling and simulation workflow

The core of the simulation consists in understanding how the two software tools interact to compute the indoor temperature in each zone, which is then compared with the experimental data collected during the monitoring campaign.

The main structure of the model is shown in Figure 4.5, where the interaction between the different components and the external data sources is highlighted. In particular, weather data are provided through an EPW file obtained from the ARPAV database, as previously discussed in Section 3.2.

For the thermal model, the main inputs are associated with the variables governing the sensible and latent heat balances within each zone, namely air temperature, humidity and solar radiation, which define the thermal and moisture conditions of the indoor environment.

The airflow model is driven by the main variables influencing natural ventilation, namely air temperature and wind. Temperature differences generate buoyancy effects (stack effect), while wind speed and direction determine pressure differences across the building envelope. Airflow rates are computed as a function of the pressure difference across each flow path. In general, the mass flow rate can be expressed as:

$$\dot{m} = C (\Delta P)^n \quad (4.1)$$

where $\dot{m}$ is the mass flow rate, C is a flow coefficient and ΔP is the pressure difference across the opening, while n is an empirical exponent depending on the flow regime. The airflow rates calculated by the airflow model are then used as inputs for the thermal model, which updates the indoor thermal conditions. This exchange is performed at each timestep, allowing the simulation of the coupled thermo-fluid dynamic behaviour of the barn.

A fixed simulation timestep of 5 minutes is adopted, consistent with the temporal resolution of the experimental data collected during the monitoring campaign. Similarly, the simulation period, from 14 November to 12 December, is defined to match the duration of the data acquisition. Additional components shown in Figure 4.5 are used for monitoring and post-processing purposes. These elements allow verification of the model behaviour during the simulation and enable the export of results, either as numerical data files (e.g., Excel format) or as graphical outputs for visualization.

4.2.4 Model validation and calibration

The model performance was evaluated through an iterative calibration process based on a trial-and-error approach. The agreement between measured and simulated data is evaluated using three statistical indicators: the Root Mean Square Error (RMSE), the Normalized Mean Bias Error (NMBE), and the Coefficient of Variation of the RMSE (CV(RMSE)).

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n}} \quad (4.2)$$

$$NMBE = \frac{\sum_{i=1}^n (M_i - S_i)}{(n - p) \bar{M}} \cdot 100 \quad (4.3)$$

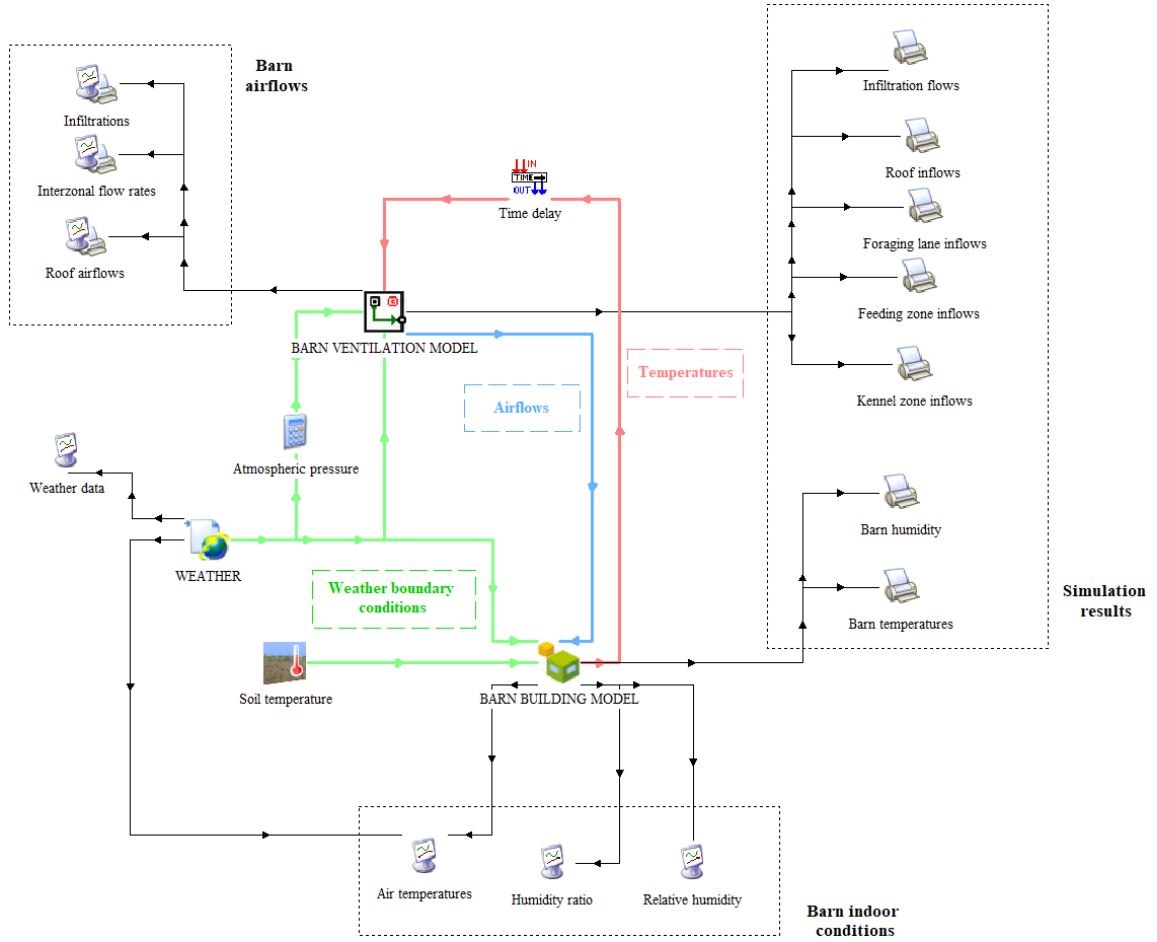


Figure 4.5: Simulation workflow and coupling between TRNSYS (building model) and CONTAM (airflow model)

$$CV(RMSE) = \frac{1}{\bar{M}} \sqrt{\frac{\sum_{i=1}^n (M_i - S_i)^2}{n - p}} \cdot 100 \quad (4.4)$$

where M_i is the measured value at timestep i , S_i is the simulated value at timestep i , n is the number of data points, p is the number of adjusted model parameters, and $\bar{M}$ is the mean of the measured values.

The RMSE provides a measure of the average magnitude of the error between measured and simulated data, giving greater weight to large deviations due to the quadratic formulation. The NMBE indicates the systematic bias of the model, showing whether the simulation tends to overestimate or underestimate the measured values. The CV(RMSE) expresses the dispersion of the error relative to the mean of the measured data, allowing a normalized assessment of the model performance. The comparison was carried out between the indoor air temperatures measured during the monitoring campaign and those predicted by the simulation model.

The measured air temperature for each zone is obtained by averaging the values recorded by the sensors installed within that specific area. An arithmetic mean is computed at each timestep in order to derive a representative temperature for the zone, which is then used for comparison

with the simulation results.

The target values for the validation indices were selected according to ASHRAE Guideline 14 [51], which recommends values of NMBE below 10% and CV(RMSE) below 30% for hourly data. During the calibration process, not all model parameters could be adjusted. External boundary conditions, such as weather data, were fixed. Therefore, the calibration focused primarily on airflow-related parameters, in particular infiltration rates. Limited adjustments were also made to internal gains associated with the presence of cattle. However, based on information provided by the farmer, animals spend most of their time in the freestall area, which constrained the variability of this parameter. After several iterations, an acceptable agreement between simulated and measured temperatures was achieved, with the model accurately reproducing the temporal trend of the experimental data. The final calibrated leakage values are reported in Table 4.6.

Table 4.6: Calibrated leakage area values used in the CONTAM model

Opening type	Leakage area [cm^2/m]
Windows	28
Wooden doors	63
Overhead door	200

Initially, a key modelling issue concerned the representation of the overhead door. According to the farmer, the door is opened twice a day during feeding and inspection activities. Therefore, a time-dependent schedule was initially implemented in the model. However, this approach led to unstable and unrealistic simulation results. The short opening duration and the uncertainty in the exact opening times made it difficult to accurately reproduce the real behaviour. For this reason, the door was ultimately assumed to remain closed, while a higher equivalent infiltration rate was assigned to account for its contribution to air exchange. Another

Table 4.7: Statistical indicators used for model validation over the monitoring period from 14/11 to 30/11. The acceptance criteria are $|NMBE| \leq 10\%$ and $CV(RMSE) \leq 30\%$, according to ASHRAE Guideline 14.

Zone	RMSE [°C]	MBE [°C]	NMBE [%]	CV(RMSE) [%]
Feed delivery alley	3.02	2.21	31.51	43.01
Feeding alley	2.15	0.09	1.31	30.08
Freestall	2.02	-0.13	-1.67	26.40

critical aspect emerged in the *feed delivery alley*, which shows the largest discrepancies between simulated and measured data, as reported in Table 4.7. This zone represents the main source of error in the model. This discrepancy can be partially explained by the sensor positioning. The sensor was located close to the entrance, making it highly sensitive to external conditions. In addition, only one sensor was installed in this area, which may not be representative of the average thermal conditions of the entire zone. Despite these limitations, this issue provided useful insights for improving the monitoring strategy in future case studies, particularly regarding sensor placement to ensure more representative and spatially uniform measurements. Despite these limitations, the comparison between simulated and measured data shows that the model

is generally able to reproduce the overall temperature trend over time. However, noticeable discrepancies are observed, particularly during peak and minimum temperature periods. These deviations can be attributed to the inherent complexity of the real operating conditions, which are difficult to fully capture in the simulation model. In particular, as reported by the farmer, maintenance activities may have occurred during the monitoring period, requiring doors to remain open for extended periods. This likely introduced additional air exchanges that were not accounted for in the model, contributing to the observed differences between simulated and measured temperatures.

In the *feed delivery alley* zone (Figure 4.6), both NMBE (31.51%) and CV(RMSE) (43.01%) exceed the acceptable limits, indicating a significant average overestimation of the indoor temperature by the model. This suggests the presence of systematic errors, likely related to an inaccurate representation of air infiltration rates or internal heat gains within the model.

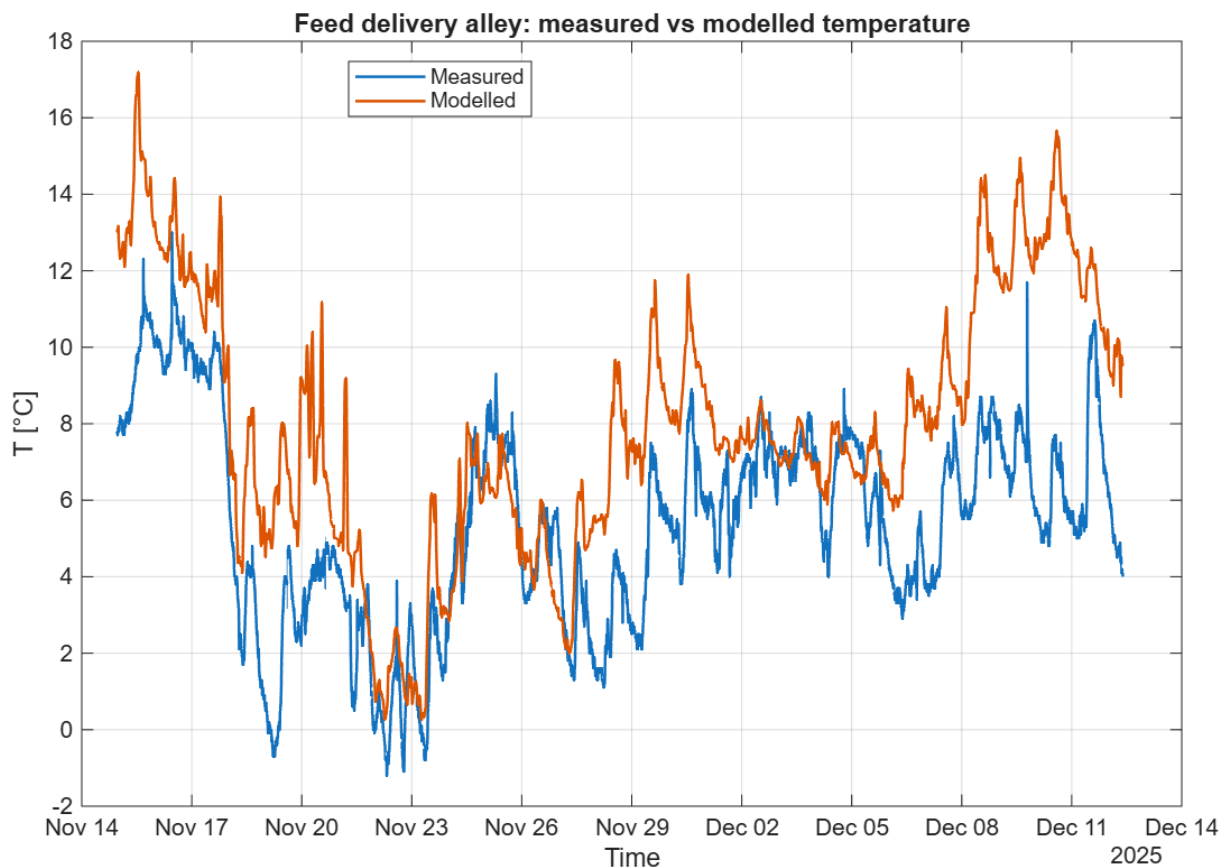


Figure 4.6: Indoor air temperature in the feed delivery alley: comparison between simulated and measured data.

In the *feeding alley* zone (Figure 4.7), the NMBE is within the acceptable range (1.31%), indicating a good agreement in terms of average values. However, the CV(RMSE) (30.08%) is slightly above the recommended threshold, highlighting a moderate dispersion between measured and simulated data. Therefore, the model can be considered reasonably accurate, although some improvements are still possible.

In the *freestall* zone (Figure 4.8), both NMBE (-1.67%) and CV(RMSE) (26.40%) meet the validation criteria, indicating a good agreement between simulated and measured temperatures.

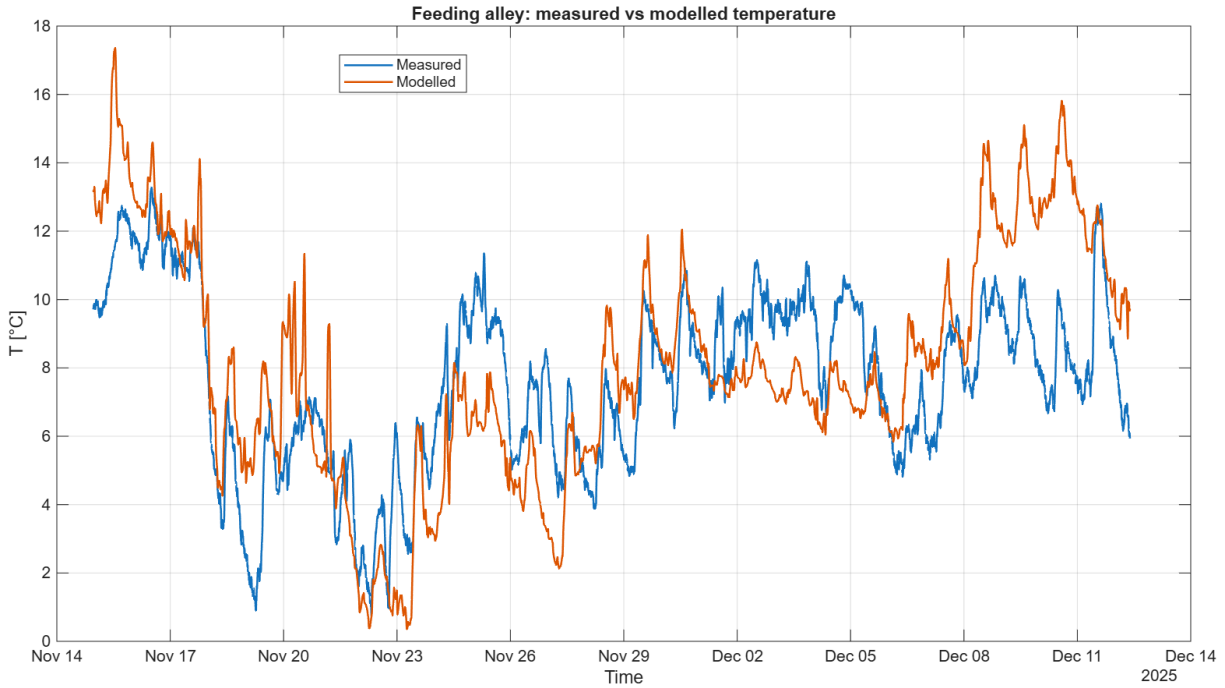


Figure 4.7: Indoor air temperature in the feeding alley: comparison between simulated and measured data.

This confirms that the model is reliable in representing the thermal behaviour of this area.

The results show different levels of accuracy depending on the analyzed zone. Overall, these results can be considered satisfactory for the purposes of this study. In particular, the model shows good agreement in the zones where cattle are predominantly located, namely the *feeding alley* and the *freestall*. This aspect is particularly relevant, as these areas are the most representative for evaluating animal thermal welfare. Therefore, despite the higher discrepancies observed in the *feed delivery alley*, which is less representative of the conditions experienced by the animals, the model can be considered sufficiently reliable for the assessment of thermal conditions to which livestock are exposed.

On this basis, the validated model was further employed to evaluate animal thermal comfort through specific indices. In particular, the Temperature–Humidity Index (THI) was calculated for each zone and compared with measured values. The calculation of both measured and simulated THI requires air temperature and relative humidity, according to the formulation proposed by Mader et al. (2006), reported in Table 1.5:

$$THI = 0.8 T_{\text{air}} + \left(\frac{RH}{100} \right) (T_{\text{air}} - 14.4) + 46.4 \quad (4.5)$$

Considering Tables 4.8 and 4.9, the statistical indicators for THI validation are well within the acceptance limits.

The feed delivery alley still shows the highest deviations among the analyzed zones; however, all indicators remain within the acceptable range defined by the guideline. Furthermore, the THI values are consistently low throughout the monitoring period, indicating the absence of heat stress conditions for the cattle. While this confirms favorable environmental conditions

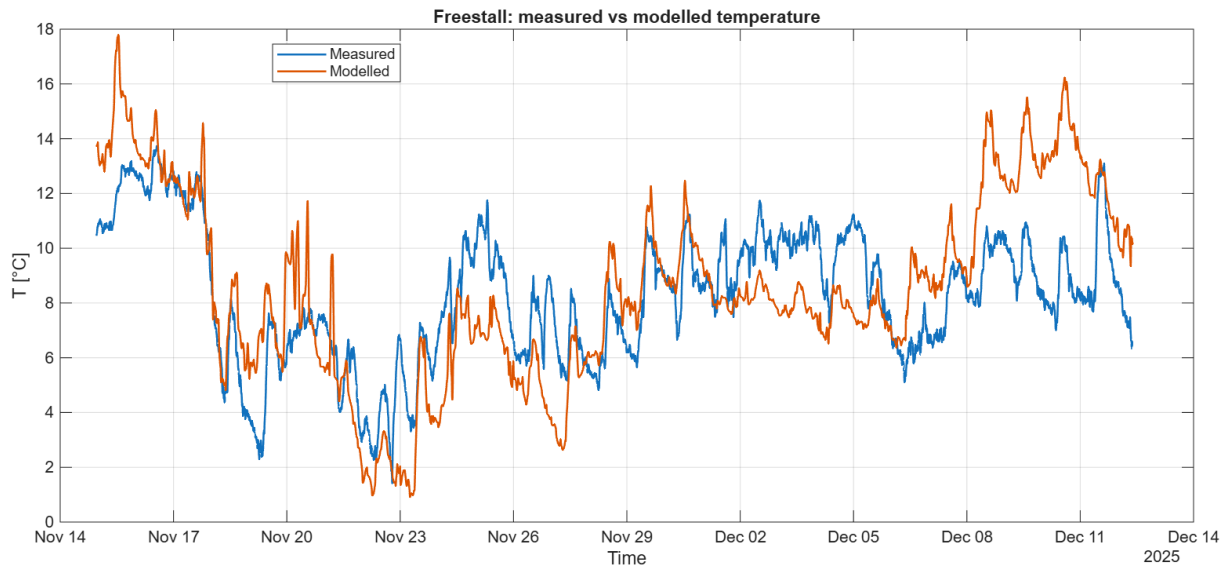


Figure 4.8: Indoor air temperature in the freestall area: comparison between simulated and measured data.

Table 4.8: Classification of heat stress levels in dairy cattle based on Temperature–Humidity Index (THI) values. The threshold values are adopted from commonly used ranges reported in the literature, as discussed in Section 1.1.4.

THI range	Heat stress level
$\text{THI} < 72$	No stress
$72 \leq \text{THI} < 79$	Mild stress
$79 \leq \text{THI} < 90$	Moderate stress
$\text{THI} \geq 90$	Severe stress

inside the barn, it also limits the possibility of evaluating the effectiveness of the additional materials under critical thermal stress scenarios. However, this outcome was expected, as the case study is located in a mountainous area characterized by relatively low temperatures. It would be particularly interesting to extend the analysis to warmer periods, such as the hottest days of 2025, to assess whether the same trends are maintained or if higher THI values and potential heat stress conditions may occur.

The comparison between measured and simulated THI values in the three zones shows a generally good agreement. The model is able to accurately reproduce the overall temporal evolution of the index, correctly capturing both the increasing and decreasing trends over time.

The main differences between measured and simulated values are related to the amplitude of the fluctuations, with the model occasionally underestimating or overestimating the peaks. However, these discrepancies are limited and do not significantly affect the overall interpretation of thermal conditions. In all zones, THI values remain well below the threshold associated with heat stress, indicating that the analysed period is characterized by thermally acceptable conditions for the livestock.

A slightly better agreement is observed in the *feeding alley* (Figure 4.10) and in the *freestall* (Figure 4.11), which are the areas most representative of the actual conditions experienced by

Table 4.9: Statistical indicators used for the validation of the Temperature–Humidity Index (THI) over the monitoring period from 14/11 to 30/11. The acceptance criteria are $|NMBE| \leq 10\%$ and $CV(RMSE) \leq 30\%$, according to ASHRAE Guideline 14.

Zone	RMSE [-]	MBE [-]	NMBE [%]	CV(RMSE) [%]
Feed delivery alley	5.03	2.96	6.38	10.85
Feeding alley	4.43	-0.76	-1.63	9.52
Freestall	4.43	-0.74	-1.55	9.34

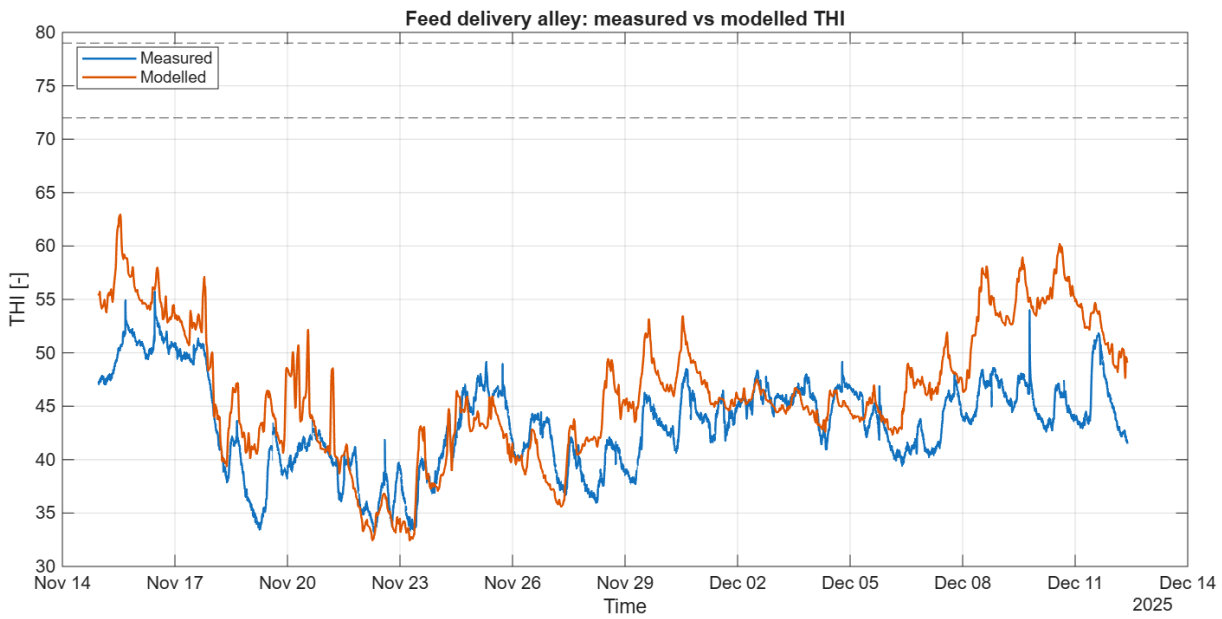


Figure 4.9: Comparison between measured and simulated Temperature–Humidity Index (THI) in the feed delivery alley. The dashed horizontal lines indicate the commonly adopted heat stress thresholds at $THI = 72$ (mild stress) and $THI = 79$ (moderate stress).

the animals. In contrast, larger deviations can be observed in the *feed delivery alley* (Figure 4.9), although their impact on the assessment of animal thermal comfort is limited.

Overall, the model proves to be reliable for evaluating livestock thermal comfort through the THI index.

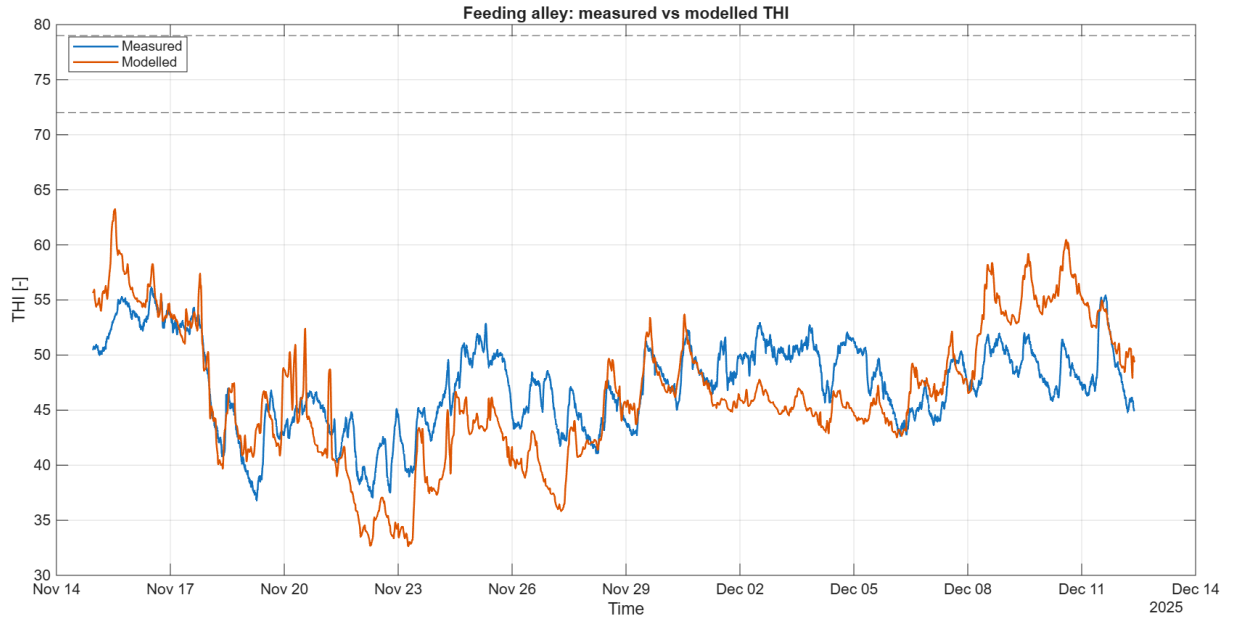


Figure 4.10: Comparison between measured and simulated Temperature–Humidity Index (THI) in the feeding alley. The dashed horizontal lines indicate the commonly adopted heat stress thresholds at $\text{THI} = 72$ (mild stress) and $\text{THI} = 79$ (moderate stress).

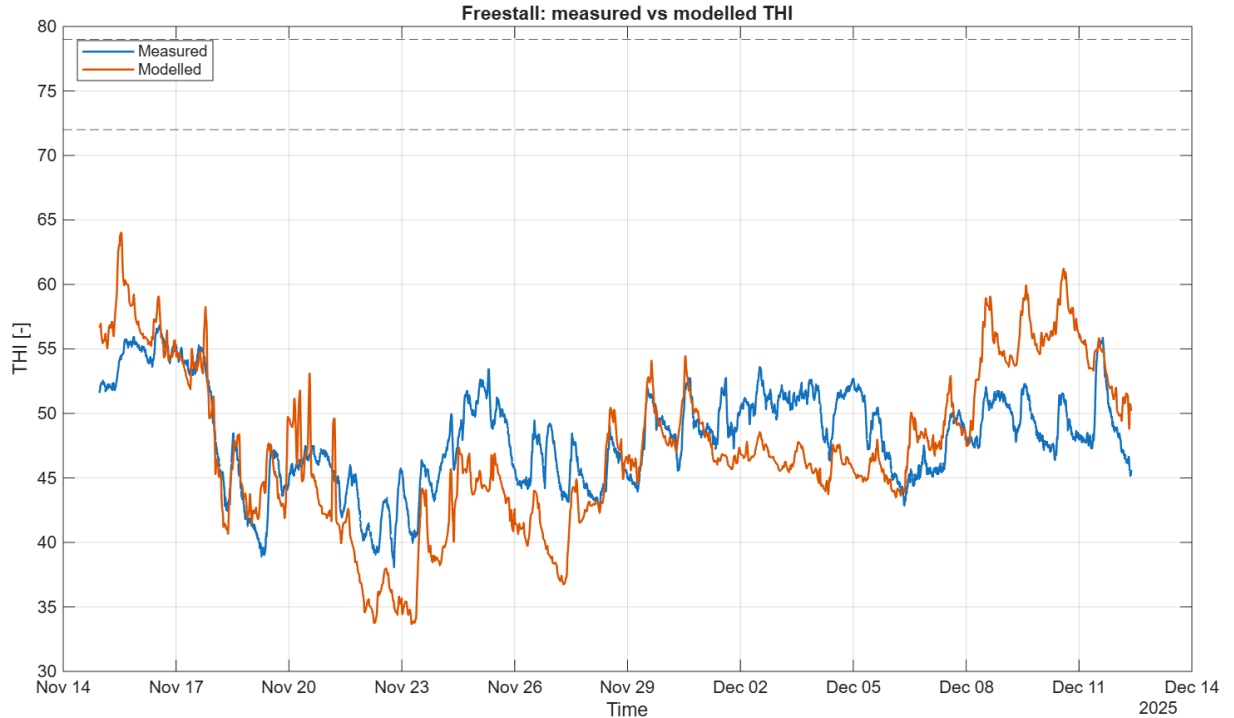


Figure 4.11: Comparison between measured and simulated Temperature–Humidity Index (THI) in the freestall area. The dashed horizontal lines indicate the commonly adopted heat stress thresholds at $\text{THI} = 72$ (mild stress) and $\text{THI} = 79$ (moderate stress).

Chapter 5

Results

The aim of this chapter is to evaluate whether different material compositions of the building envelope can improve cattle thermal welfare. The analysis was carried out over the period from 14 November to 12 December 2025, in order to assess the performance of different wall configurations under winter conditions. The following configurations were investigated:

- **Base case:** current wall configuration of the barn, with a total thickness of 39.5 cm (25 cm of P800 and 14.5 cm of insulation, as reported in Table 2.1);
- **P800 only:** wall composed entirely of Poroton P800 material, with a total thickness of 39.5 cm;
- **Added insulation:** addition of a 10 cm layer of bio-based insulating material to the existing wall, resulting in a total thickness of 49.5 cm (25 cm of P800, 14.5 cm of existing insulation, and 10 cm of bio-based material);
- **Substitution case:** replacement of the existing insulation layer with a bio-based composite solution, resulting in a wall composed of 25 cm of P800 and 14.5 cm of bio-based insulating material.

These configurations allow a comparison both between different material compositions and between different total thicknesses. The bio-based material was analysed for different compositions, corresponding to GP contents of 0%, 2.5%, 5%, 7.5%, and 10%. The associated thermophysical properties are reported in Table 1.6. The simulations were performed with a timestep of 5 minutes, allowing a high temporal resolution in the analysis. Thermal discomfort events were identified when the THI exceeded the threshold values reported in Table 4.8. With this timestep, each hour consists of 12 simulation steps, corresponding to 288 time steps per day. This approach enables the evaluation of both the duration and frequency of heat stress conditions, providing a robust basis for assessing the effectiveness of the different material configurations. The results are presented separately for winter and summer conditions. Particular attention is given to summer, as it represents the most critical scenario for cattle thermal stress.

For clarity, Table 5.1 summarizes the notation adopted for the different envelope configurations analysed in this study. The letter **A** indicates that the grape pomace-based material is *added to the existing barn envelope*, while **O** denotes configurations where the same material is *added to the P800 reference wall*.

Table 5.1: Description of envelope configurations and material notation used in the analysis

Notation	Description
BASE	Existing barn envelope (baseline configuration)
P800	Wall configuration entirely composed of Poroton P800
<i>Added configurations (A)</i>	
GP-0A	0% grape pomace added to the existing envelope
GP-2.5A	2.5% grape pomace added to the existing envelope
GP-5A	5% grape pomace added to the existing envelope
GP-7.5A	7.5% grape pomace added to the existing envelope
GP-10A	10% grape pomace added to the existing envelope
<i>Only configurations (O)</i>	
GP-0O	0% grape pomace applied to the P800 wall configuration
GP-2.5O	2.5% grape pomace applied to the P800 wall configuration
GP-5O	5% grape pomace applied to the P800 wall configuration
GP-7.5O	7.5% grape pomace applied to the P800 wall configuration
GP-10O	10% grape pomace applied to the P800 wall configuration
<i>Modified configurations (M*)</i>	
GP-5AM	Modified added configuration with adjusted heat capacity
GP-7.5AM	Modified added configuration with adjusted heat capacity
GP-10AM	Modified added configuration with adjusted heat capacity
GP-5OM	Modified only configuration with adjusted heat capacity
GP-7.5OM	Modified only configuration with adjusted heat capacity
GP-10OM	Modified only configuration with adjusted heat capacity

5.1 Winter performance analysis

The performance of the barn during winter conditions was evaluated by analysing the THI in each zone at every simulation timestep. Subsequently, the number of occurrences exceeding specific threshold values was calculated in order to assess whether critical conditions for cattle thermal stress were reached. The analysis of the THI values shows that no critical conditions for animal discomfort occur during the analysed period. For all zones and wall configurations, the index remains consistently below the threshold of 72, corresponding to no heat stress conditions. Although slight temporal variations are observed, the values never exceed the critical thresholds associated with mild, moderate or severe stress, confirming that the indoor thermal conditions remain within a comfortable range throughout the entire simulation period. An additional aspect observed during winter conditions concerns relative humidity. Indoor RH rapidly reaches saturation (100%), mainly due to the high moisture production associated with cattle respiration. This behaviour suggests limited moisture removal through ventilation, although it does not lead to thermal stress conditions according to the THI index.

Table 5.2: Winter: Summary of THI results for different wall configurations and zones

Structure	Average THI	Max THI	>60
Baseline configurations			
Normal Wall – Feeding alley	47.3	56.1	0
Normal Wall – Freestall	48.2	56.8	0
P800 – Feeding alley	46.5	63.4	68
P800 – Freestall	47.3	64.1	113
Adding GP			
Adding GP0 – Feeding alley	46.6	63.3	65
Adding GP0 – Freestall	47.5	64.1	123
Adding GP2.5 – Feeding alley	46.6	63.3	65
Adding GP2.5 – Freestall	47.5	64.1	123
Adding GP5 – Feeding alley	46.6	63.3	65
Adding GP5 – Freestall	47.5	64.1	121
Adding GP7.5 – Feeding alley	46.6	63.3	65
Adding GP7.5 – Freestall	47.5	64.0	119
Adding GP10 – Feeding alley	46.6	63.3	65
Adding GP10 – Freestall	47.5	64.0	122
Only GP			
Only GP0 – Feeding alley	46.4	63.2	57
Only GP0 – Freestall	47.3	63.9	100
Only GP2.5 – Feeding alley	46.4	63.2	57
Only GP2.5 – Freestall	47.3	63.9	100
Only GP5 – Feeding alley	46.4	63.1	57
Only GP5 – Freestall	47.3	63.9	102
Only GP7.5 – Feeding alley	46.4	63.2	63
Only GP7.5 – Freestall	47.3	64.0	106
Only GP10 – Feeding alley	46.5	63.2	62
Only GP10 – Freestall	47.3	64.0	104

Since no occurrences were detected within the standard heat stress thresholds, a lower reference value was introduced to further investigate the system behaviour. In particular, a THI value of 60 was selected as a reference threshold to identify the onset of deviations among the different zones. Table 5.2 reports, for each configuration and zone, the average THI, the maximum THI, and the number of occurrences with THI values greater than 60. Since the evaluation of Temperature Humidity Index is relevant only in areas where cattle are present, the analysis focuses on the feeding alley (*Alimentazione*) and the freestall (*Cucce*). The number of occurrences associated with the different configurations is very similar across all cases. However, it is worth noting that the base wall configuration, without additional insulation, shows the best performance, as it is the only case with zero occurrences of Temperature Humidity Index (THI) values exceeding 60. Therefore, under winter conditions, the addition of an insulation layer slightly increases the frequency of such events, indicating a marginal reduction in animal thermal comfort. Nevertheless, this difference is negligible: approximately 200 occurrences, summed over the two areas, correspond to about 17 hours over an entire month, and can therefore be considered insignificant in practical terms. Moreover, it should be noted that THI values above 60 do not necessarily indicate heat stress conditions, according to the adopted classification.

5.2 Summer thermal stress analysis

The most relevant analysis was carried out for the summer period, as it represents the most critical condition for cattle thermal comfort. The three hottest consecutive weeks of 2025 were selected using climate data obtained from the ARPAV database. The selected period spans from June 13th to July 3rd. After setting up the model in TRNSYS Simulation Studio, the results were exported and analysed in Excel for the different wall configurations.

Similarly to the winter case, in the simulation the leakage characteristics are kept unchanged, and no modifications are applied to the opening conditions of doors and windows, which in reality could be more appropriate during the summer period. This represents a modelling assumption.

A key difference compared to the winter case is the behaviour of relative humidity. During summer, RH varies throughout both the day and the analysed period, and does not remain saturated at 100%. In addition, the higher air temperatures lead to significantly higher values of Temperature Humidity Index, allowing the identification of thermal stress conditions. The analysis of the THI values highlights several periods during which cattle are exposed to heat stress conditions. In this case, the influence of the different wall configurations becomes more evident compared to the winter scenario.

An additional modification was introduced in the simulations concerning the thermophysical properties of the materials. In particular, for the configurations containing 5%, 7.5%, and 10% of Grape pomace, the experimentally measured heat capacity values showed limited consistency with the expected physical behaviour. Therefore, a value of 0.9 kJ/(kg K) was adopted for these materials in order to ensure a more consistent representation of their thermal behaviour. These modified configurations are labelled with “M*” in the following table. Further experimental investigations are required to better characterise the thermal capacity of these composite materials. The effective heat capacity is expected to reflect a weighted contribution of the individual components and should therefore lie within the range defined by the constituent materi-

als. Consequently, values lower than those of all the constituent materials would be physically inconsistent.

5.2.1 Feeding Alley Heat Stress Analysis

This section provides a detailed analysis of heat stress conditions by focusing exclusively on the feeding alley. Unlike the aggregated evaluation across multiple zones, this approach allows a direct interpretation of the actual exposure time experienced by the animals.

Table 5.3: Number of heat stress occurrences in the feeding alley for each configuration

Structure	$72 \leq \text{THI} < 79$	$79 < \text{THI} \leq 90$	$\text{THI} > 90$	Total
Baseline configurations				
Normal Wall	3734	1128	0	4862
P800	3655	1135	0	4790
Adding GP				
Adding GP0	3743	1127	0	4870
Adding GP2.5	3743	1128	0	4871
Adding GP5	3743	1127	0	4870
Adding GP7.5	3741	1128	0	4869
Adding GP10	3745	1127	0	4872
Only GP				
Only GP0	3686	1115	0	4801
Only GP2.5	3689	1114	0	4803
Only GP5	3679	1116	0	4795
Only GP7.5	3636	1125	0	4761
Only GP10	3676	1124	0	4800
Modified cases (M*)				
Adding GP5 M*	3743	1128	0	4871
Only GP5 M*	3689	1115	0	4804
Adding GP7.5 M*	3745	1127	0	4872
Only GP7.5 M*	3696	1114	0	4810
Adding GP10 M*	3745	1127	0	4872
Only GP10 M*	3716	1115	0	4831

As reported in Table 5.3, the total number of occurrences for the baseline configuration (Normal Wall) is 4862 events. This corresponds to approximately 405 hours, i.e., nearly 17 days of heat stress over the three-week simulation period.

The mild heat stress range ($72 \leq \text{THI} < 79$) accounts for approximately 76% of the total occurrences, corresponding to about 311 hours of exposure.

These results highlight that cattle are exposed to prolonged sub-optimal thermal conditions during the analysed period (June 13th to July 3rd).

For a clearer interpretation of the results, the analysed configurations are compared with the baseline structure in order to assess whether any improvement in thermal conditions can be observed.

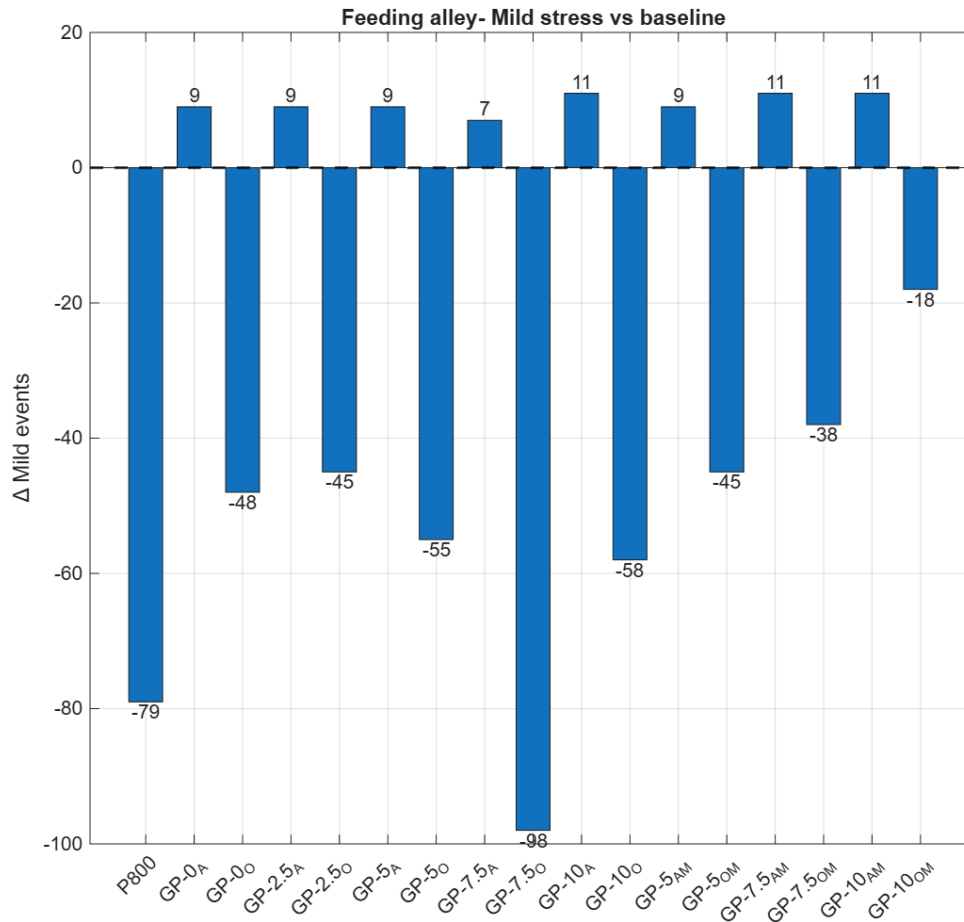


Figure 5.1: Variation in the number of mild heat stress events in the feeding alley for different envelope configurations, expressed as deviation from the baseline case. Negative values indicate a reduction in mild stress events compared to the baseline, while positive values indicate an increase.

Starting from Figure 5.1, which shows the comparison of different materials under mild heat stress conditions ($72 \leq \text{THI} < 79$) in the feeding alley, it can be observed that adding the material to the baseline structure leads to a slight increase in the number of stress events within the barn.

However, the magnitude of this increase is very limited. For instance, an increase of about 10 events corresponds to less than one hour over the entire simulation period and can therefore be considered negligible.

The most significant reduction is observed when the material is used alone. In particular, the GP 7.5% configuration shows a notable decrease in mild stress events, corresponding to a reduction of approximately 8 hours.

Apart from the P800 configuration, which achieves a reduction of nearly 7 hours, the other configurations exhibit similar behaviour, with reductions of approximately 4 hours of mild heat stress.

It is also interesting to analyse the gradual increase in the number of stress events observed in the modified materials compared to the corresponding base materials. In these modified configurations, where the heat capacity is kept constant but the density varies, it can be observed that configurations characterized by lower thermal conductivity and lower density tend to exhibit a slight increase in the number of events. This behaviour suggests that reduced heat transfer through the envelope may limit heat dissipation, leading to a marginal worsening of indoor thermal conditions.

Overall, the differences between configurations remain relatively small in absolute terms, indicating that, although material modifications can influence thermal conditions, their impact in the feeding alley is limited under the analysed summer conditions.

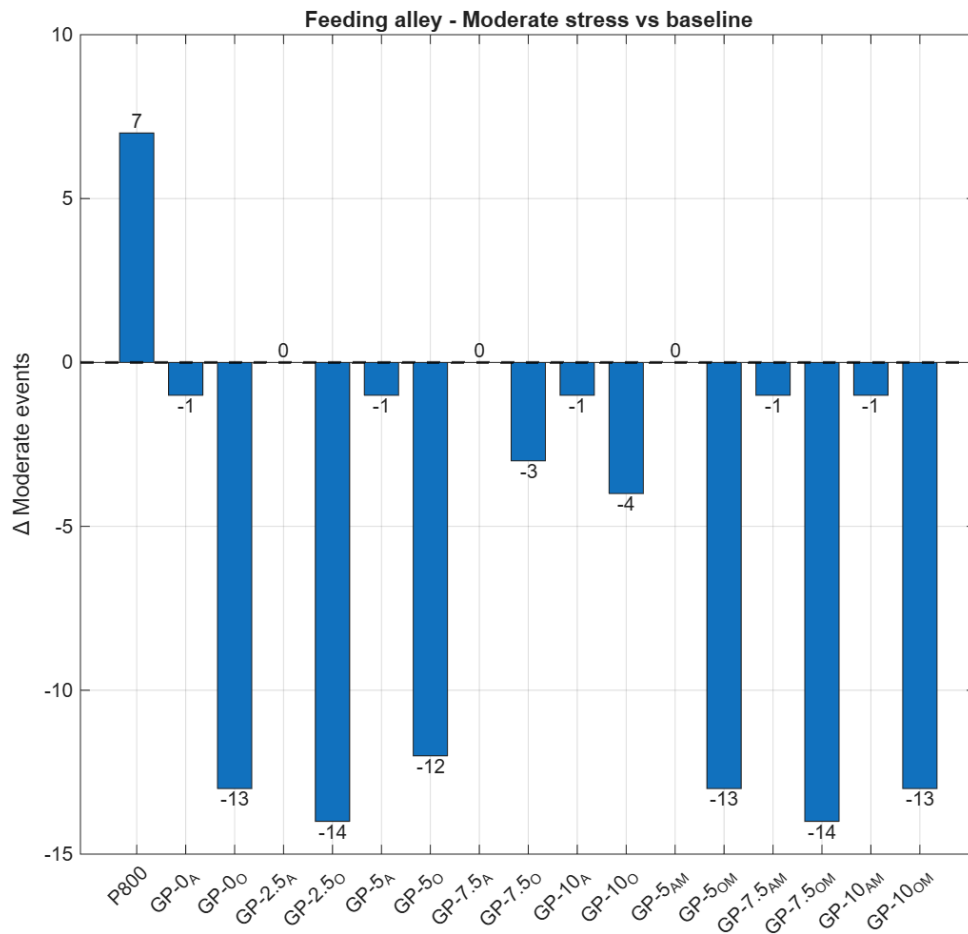


Figure 5.2: Variation in the number of moderate heat stress events in the feeding alley for different envelope configurations, expressed as deviation from the baseline case. Negative values indicate a reduction in mild stress events compared to the baseline, while positive values indicate an increase.

The analysis is now extended to moderate heat stress conditions ($79 < \text{THI} \leq 90$) in feeding alley (Figure 5.2).

A first relevant observation is that the P800 configuration shows the highest number of events, with 7 more occurrences than the baseline wall. This corresponds to less than one hour of additional heat stress over the entire simulation period, indicating only a marginally negative

effect of this material under more severe thermal conditions.

In contrast with the previous analysis on mild stress, the addition of insulating material to the existing wall does not lead to a worsening of thermal conditions. On the contrary, the number of events remains nearly unchanged, or in some cases is reduced by a single occurrence. However, such differences are negligible, as they correspond to a single timestep (5 minutes) and therefore do not represent a meaningful variation.

Overall, adding an additional insulation layer with different compositions does not produce significant differences under moderate heat stress conditions.

More noticeable variations are observed when considering configurations based on P800 combined with a grape pomace (GP) insulation layer. In this case, the configurations with 7.5% and 10% GP show values comparable to the baseline, representing the least favourable cases within this group.

The remaining configurations exhibit a slight reduction in the number of events, corresponding to approximately one hour of decreased heat stress over the entire simulation period. Although limited, this suggests a small potential benefit associated with certain material combinations.

It should be noted that these results refer to a well-insulated barn located in a mountainous region, where external conditions are relatively moderate. Therefore, the impact of envelope modifications may be more pronounced under different climatic conditions. However, this consideration remains speculative and would require further analysis to be confirmed.

The last figure to be analysed refers to the total reduction of heat stress events in the feeding alley. As shown in Figure 5.3, the configuration that provides the greatest reduction in the total number of events, considering both mild and moderate stress, is the one combining the P800 wall with a 7.5% grape pomace (GP) layer.

This result is consistent with the previous discussion, where it was observed that the dominant contribution to the overall reduction is associated with mild heat stress, while no significant improvement was detected in the moderate stress range.

Therefore, it can be stated that this configuration allows a reduction of approximately 8.5 hours of heat stress over the analysed period in the feeding alley. The other configurations show a reduction of approximately 5 hours.

Although the differences between configurations are not particularly large, a consistent reduction in total heat stress events is observed. This suggests that the proposed material can represent a viable alternative to the current envelope configuration.

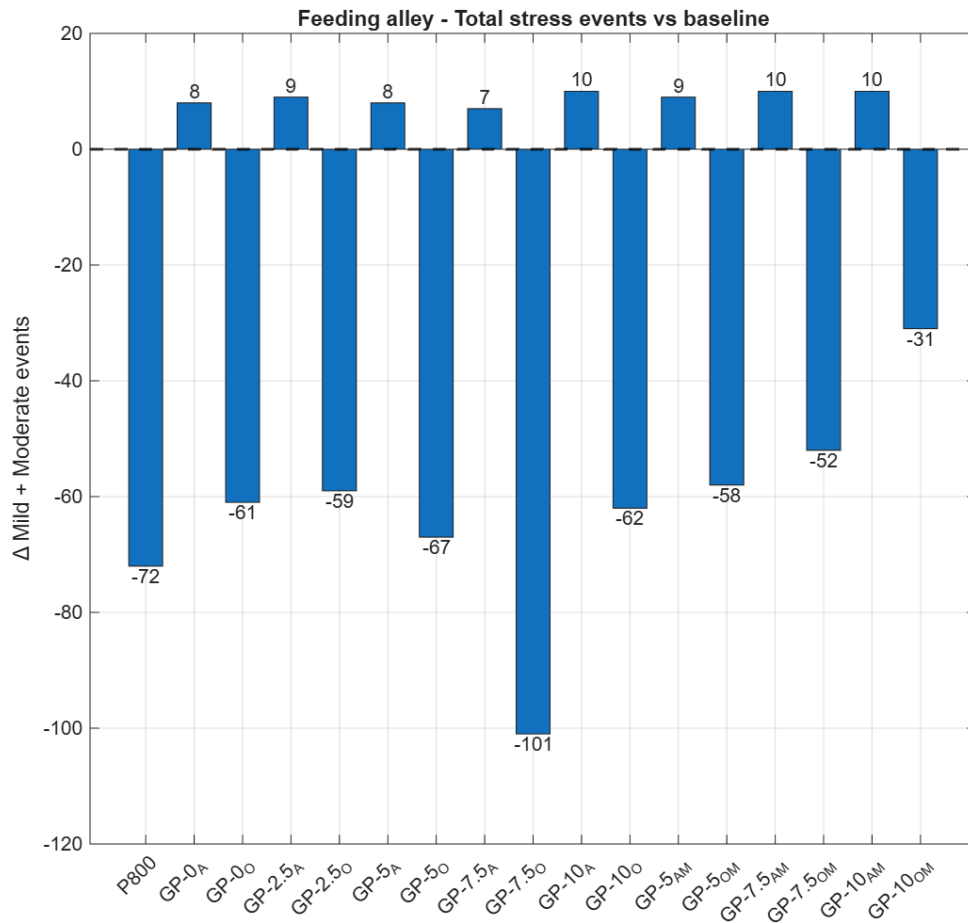


Figure 5.3: Variation in the total number of heat stress events (mild + moderate) in the feeding alley area for different envelope configurations, expressed as deviation from the baseline case. Negative values indicate an overall reduction in heat stress events, suggesting improved thermal conditions for the animals.

5.2.2 Freestall Area Heat Stress Analysis

The freestall area is the zone where cattle spend most of their time. For this reason, a higher number of heat stress events is expected, due to the greater heat generation associated with animal presence.

It is also interesting to observe that the distribution of heat stress occurrences is not uniform among the THI classes. In particular, moderate heat stress conditions ($79 < \text{THI} \leq 90$) account for approximately 29% of the total events, while mild heat stress conditions ($72 \leq \text{THI} \leq 79$) represent about 71%. This indicates that, although mild stress is more frequent, a significant portion of the time the animals are exposed to moderate heat stress conditions in this area.

In terms of duration, this corresponds to more than 18 days of heat stress over the three-week simulation period. This value is slightly higher than that observed in the feeding alley (approximately 17 days), confirming that the freestall area represents the most critical zone in terms of animal exposure to heat stress.

Table 5.4: Number of heat stress occurrences for each wall configuration in the freestall area

Structure	$72 \leq \text{THI} \leq 79$	$79 < \text{THI} \leq 90$	$\text{THI} > 90$	Total
Baseline configurations				
Normal Wall	3714	1515	0	5229
P800	3664	1524	0	5188
Adding GP				
Adding GP0	3721	1515	0	5236
Adding GP2.5	3721	1515	0	5236
Adding GP5	3721	1515	0	5236
Adding GP7.5	3719	1516	0	5235
Adding GP10	3717	1518	0	5235
Only GP				
Only GP0	3697	1493	0	5190
Only GP2.5	3699	1492	0	5191
Only GP5	3693	1494	0	5187
Only GP7.5	3664	1515	0	5179
Only GP10	3674	1514	0	5188
Modified cases (M*)				
Adding GP5 M*	3721	1515	0	5236
Only GP5 M*	3697	1494	0	5191
Adding GP7.5 M*	3722	1515	0	5237
Only GP7.5 M*	3702	1494	0	5196
Adding GP10 M*	3718	1519	0	5237
Only GP10 M*	3711	1494	0	5212

Focusing on mild heat stress conditions ($72 \leq \text{THI} \leq 79$) in the freestall area(Figure 5.4), the addition of material to the baseline configuration leads to a slight increase in the number of

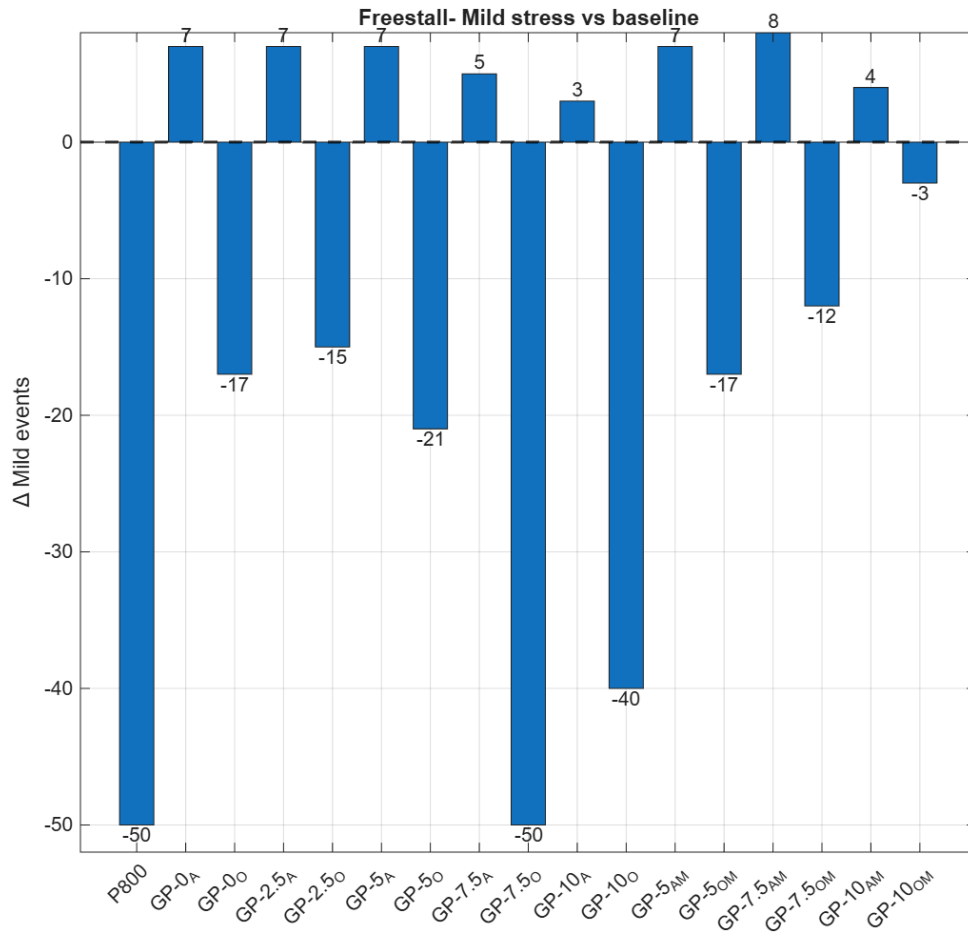


Figure 5.4: Variation in the number of mild heat stress events in the freestall for different envelope configurations, expressed as deviation from the baseline case. Negative values indicate a reduction in mild stress events compared to the baseline, while positive values indicate an increase.

events; however, this variation is negligible due to its limited magnitude, corresponding to less than one hour over the entire simulation period.

In contrast, configurations based on the substitution of the existing wall with P800 or with bio-based materials applied to the P800 layer show a reduction in the number of events. In particular, the GP 7.5% configuration achieves the best result, with a reduction of more than 4 hours of mild heat stress. Another configuration showing a significant improvement is GP 10%, with a reduction exceeding 3 hours.

The remaining configurations exhibit smaller reductions, ranging between approximately 15 and 20 events, corresponding to about 1 to less than 2 hours.

The modified configurations (M*) exhibit behaviour consistent with the corresponding base materials, with only minor variations in the number of events. Since the heat capacity values of the materials are relatively similar, while the main variation concerns thermal conductivity, the limited differences observed suggest that variations in thermal conductivity alone have a relatively small influence on heat stress conditions in the analysed context.

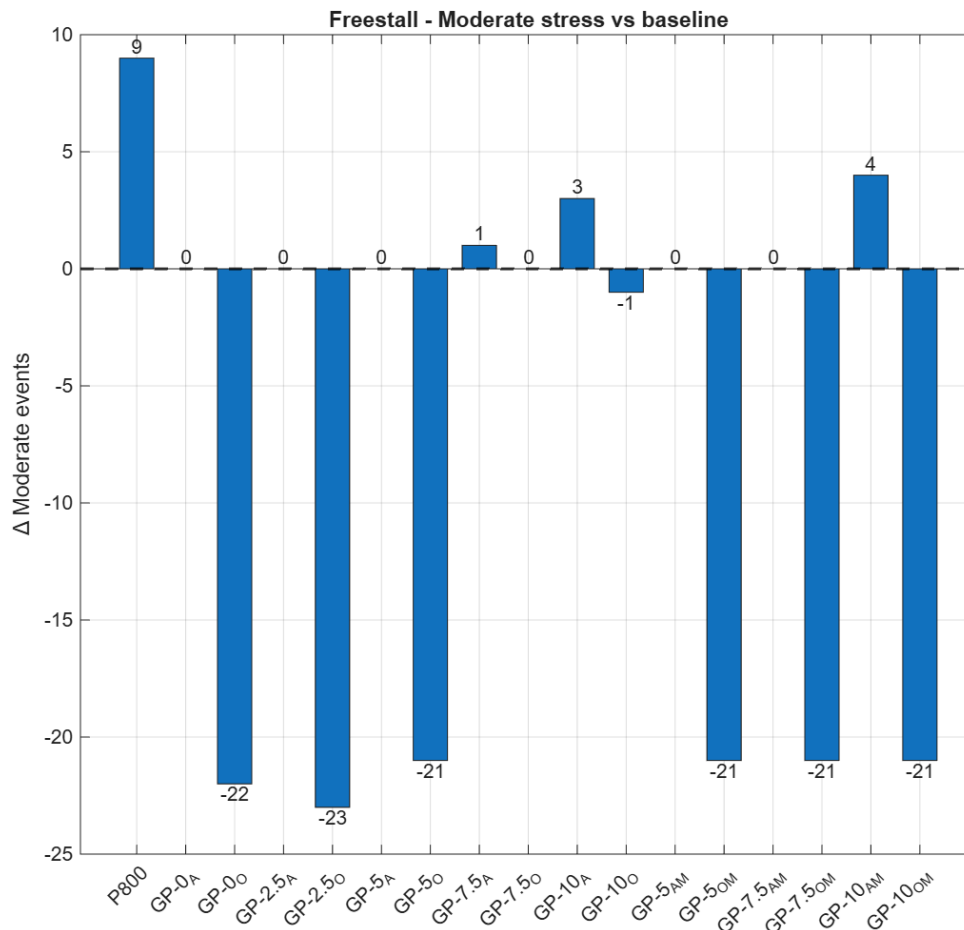


Figure 5.5: Variation in the number of moderate heat stress events in the freestall for different envelope configurations, expressed as deviation from the baseline case. Negative values indicate a reduction in mild stress events compared to the baseline, while positive values indicate an increase.

Considering moderate heat stress conditions ($79 < \text{THI} \leq 90$) in the freestall area (Figure

5.5), which are more critical for animal welfare, a different behaviour emerges. The P800 configuration shows a slight increase in the number of events compared to the baseline case, corresponding to about 9 additional events (less than one hour over the entire simulation period).

The configurations with the addition of bio-based layers to the baseline structure show values very close to the baseline case, indicating a negligible effect. On the other hand, the substitution configurations (P800 and GP materials applied to P800) lead to a reduction of approximately 22 events, corresponding to nearly 2 hours less of moderate heat stress.

The modified configurations (M*) follow the same trend, showing results comparable to those of the corresponding base materials. This suggests that the small variations in thermal conductivity do not significantly affect the number of moderate heat stress events.

Overall, these results indicate that the proposed materials provide a consistent response under more severe heat stress conditions, contributing to a slight reduction in moderate heat stress events within the barn.

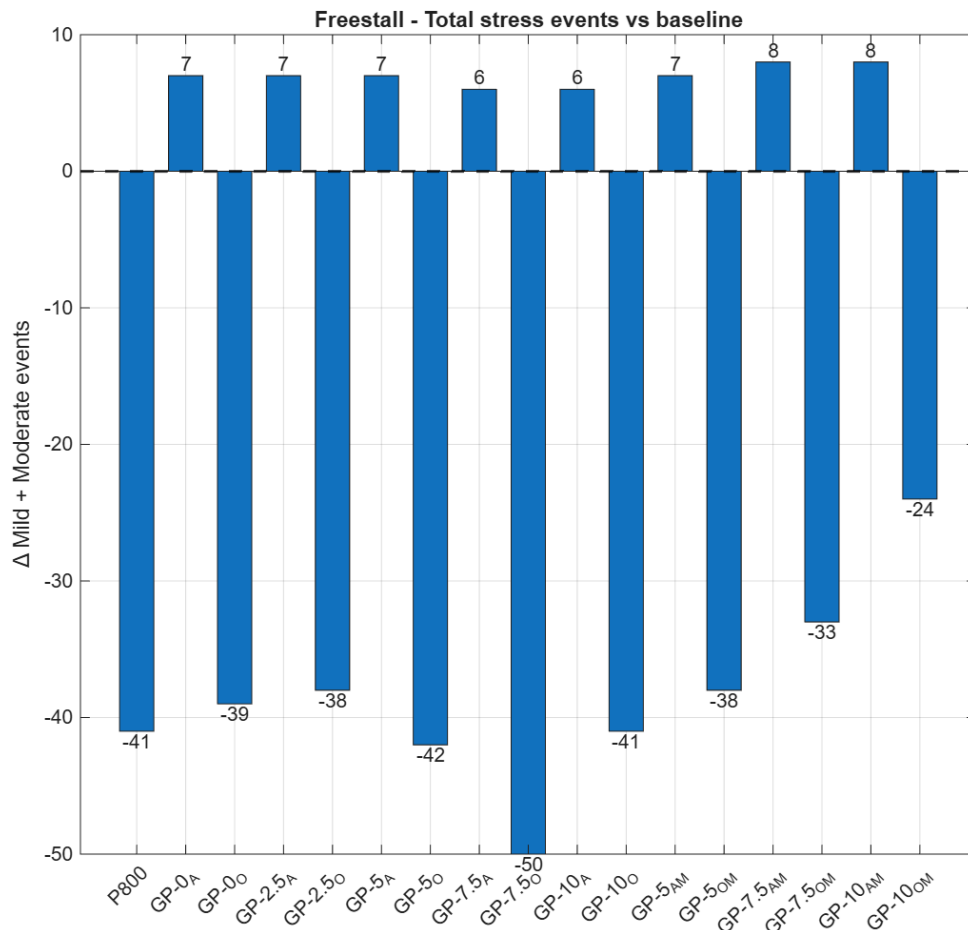


Figure 5.6: Variation in the total number of heat stress events (mild + moderate) in the freestall area for different envelope configurations, expressed as deviation from the baseline case. Negative values indicate an overall reduction in heat stress events, suggesting improved thermal conditions for the animals.

From the Figure 5.6, it can be observed that, overall, the addition of bio-based material to the existing freestall envelope leads to a slight increase in the total number of heat stress events,

corresponding to less than one hour over the entire simulation period.

In contrast, when considering configurations based on P800 + grape pomace (GP), a reduction in the total number of events is observed. In particular, the GP 7.5% configuration shows the best performance, with a reduction slightly greater than 4 hours. The other configurations exhibit similar behaviour.

An exception is represented by the modified cases (M*), in which the heat capacity is kept constant while the density decreases with increasing GP content. In these cases, an increase in the number of events is observed in the freestall area.

Overall, the differences between configurations remain limited, generally within approximately one hour. This indicates that, although material modifications influence the thermal response, their impact on total heat stress events in the freestall area remains relatively small.

Furthermore, by comparing the results with those obtained in the feeding alley (Table 5.5), i.e., by evaluating the difference between the number of events in the freestall and in the feeding alley, it can be observed that, under moderate heat stress conditions ($79 < \text{THI} \leq 90$), all the analysed configurations exhibit a predominance of heat stress events in the freestall area compared to the feeding alley.

A different behaviour is observed for mild heat stress conditions ($72 \leq \text{THI} \leq 79$). When bio-based material is added to the existing envelope, the freestall shows fewer events compared to the feeding alley. Conversely, when considering configurations based on P800 combined with bio-based materials, the freestall tends to exhibit a higher number of events than the feeding alley.

The results show a consistent increase in the total number of events in the freestall compared to the feeding alley. This difference corresponds to more than one full day (approximately 30.5 hours) of additional heat stress exposure.

Moreover, this increase is mainly associated with the moderate heat stress range ($79 < \text{THI} \leq 90$), indicating that the worsening of thermal conditions in the freestall is primarily driven by more severe stress levels rather than mild ones.

Table 5.5: Difference in the number of heat stress occurrences between the freestall area and the feeding alley for each wall configuration, subdivided by THI range. Positive values indicate a higher number of events in the freestall area, while negative values indicate a higher number of events in the feeding alley.

Structure	$72 \leq \text{THI} \leq 79$	$79 < \text{THI} \leq 90$	$\text{THI} > 90$	Total delta
Normal Wall	-20	387	0	367
P800	9	389	0	398
Adding GP0	-22	388	0	366
Only GP0	11	378	0	389
Adding GP2.5	-22	387	0	365
Only GP2.5	10	378	0	388
Adding GP5	-22	388	0	366
Only GP5	14	378	0	392
Adding GP7.5	-22	388	0	366
Only GP7.5	28	390	0	418
Adding GP10	-28	391	0	363
Only GP10	-2	390	0	388
Adding GP5 M*	-22	387	0	365
Only GP5 M*	8	379	0	387
Adding GP7.5 M*	-23	388	0	365
Only GP7.5 M*	6	380	0	386
Adding GP10 M*	-27	392	0	365
Only GP10 M*	-5	379	0	381

5.2.3 Effect of thickness on the performance of modified materials

As already discussed, the data related to the heat capacity of GP 5, 7.5 and 10 show some values that do not reflect the expected physical behaviour. Since these materials are composed of different components, their heat capacity should result from a weighted average and should not fall below a certain threshold. Therefore, for the configurations presenting unrealistically low values, an average heat capacity of 0.9 kJ/(kg K) was assumed.

In this subsection, the behaviour of the model is analysed by varying the thickness of the insulated material added to the P800 layer. Based on the previous analyses, it is expected that reducing the thickness will lead to a decrease in the number of mild heat stress events and, conversely, to an increase in moderate heat stress events. This behaviour is consistent with the reduction of the thermal inertia of the envelope as the thickness decreases. The comparison is carried out between the configurations already discussed, with a thickness of 14.5 cm, and those with a reduced thickness of 7 cm. These are also compared with baseline configurations in order to better highlight the differences.

The first comparison is presented in Figure 5.7, where the two thicknesses are compared with respect to the baseline configuration in the freestall area, focusing on mild heat stress conditions.

It can be observed that, under mild stress conditions, the 7 cm configuration leads to a reduction in the number of negative events of approximately 2 hours in the freestall area.

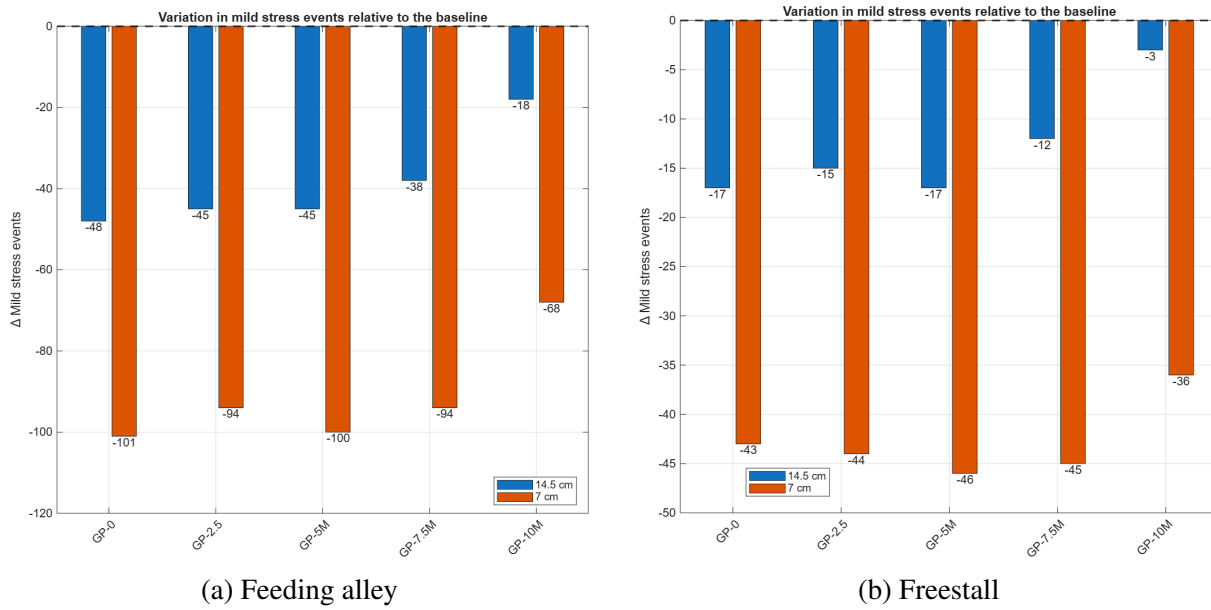


Figure 5.7: Mild heat stress events ($72 \leq \text{THI} \leq 79$) in feeding alley and freestall

A more pronounced effect is observed in the feeding alley, where the reduction in the number of events is significantly greater. In particular, the 7 cm configuration results in a reduction of approximately 8 hours, while the 14.5 cm configuration shows a reduction of about 4 hours.

Figure 5.8 shows that, under moderate heat stress conditions, the configuration with the greater thickness performs better in both zones, namely the freestall and the feeding alley.

For the 7 cm configuration, the reduction in heat stress events is limited in both areas, amounting to less than one hour. In contrast, the 14.5 cm configuration shows a more pronounced improvement, with a reduction of nearly 2 hours in the freestall area and slightly more than 1 hour in the feeding alley.

This behaviour highlights a trade-off associated with the thermal inertia of the envelope. Lower thickness (7 cm) reduces thermal inertia, allowing the structure to respond more rapidly to external conditions, which results in a reduction of mild heat stress events.

Conversely, higher thickness (14.5 cm) increases thermal inertia, improving the damping of peak temperatures and leading to better performance under moderate heat stress conditions.

Figure 5.9 shows that, when combining mild and moderate heat stress events, the 7 cm configuration performs better than the 14.5 cm configuration. In both the feeding alley and the freestall area, the 7 cm thickness leads to a reduction in the total number of events compared to the thicker configuration.

Therefore, it can be concluded that, between the two analysed solutions, the configuration with 7 cm of insulation material added to the P800 wall provides the most favourable performance in terms of total heat stress reduction.

This suggests that, under the analysed summer conditions, the reduction in mild heat stress events plays a dominant role in determining the overall performance, outweighing the benefits observed for moderate stress with higher thickness.

Tables 5.6 and 5.7 report the differences between the two thicknesses. Positive values indicate a higher number of events for the 14.5 cm configuration, while negative values indicate a higher number of events for the 7 cm configuration. Overall, the results show that reducing the

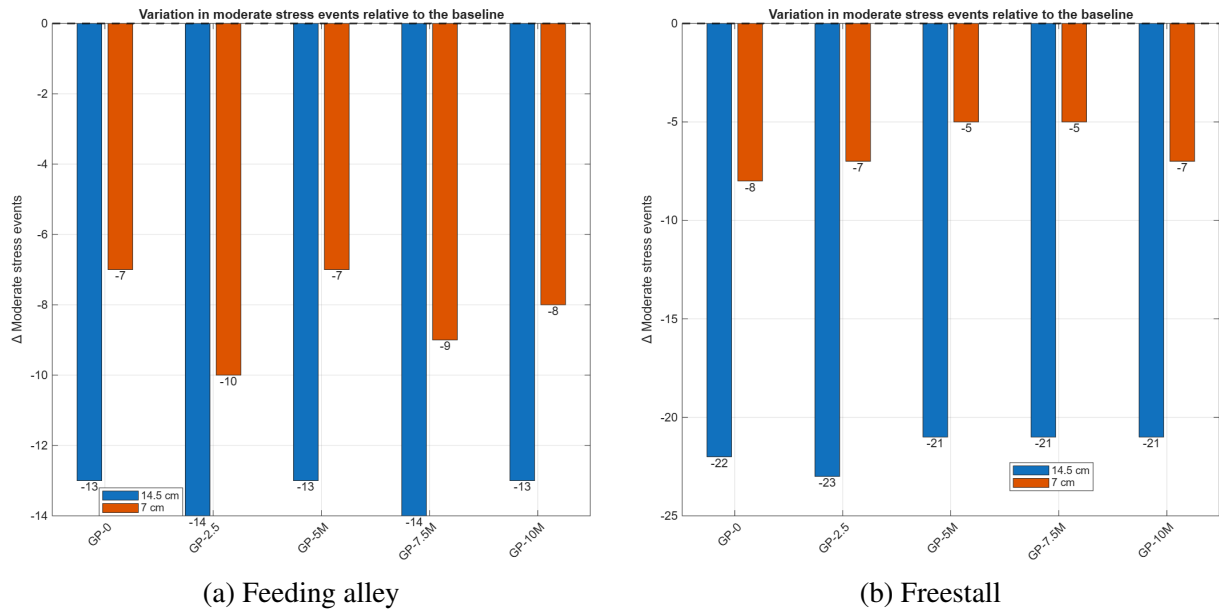


Figure 5.8: Moderate heat stress events ($79 < \text{THI} \leq 90$) in feeding alley and freestall

Table 5.6: Difference in the number of heat stress events between configurations with thickness of 14.5 cm and 7 cm in the feeding alley

Configuration	Δ Mild	Δ Moderate	Δ Severe	Δ Total
GP0	+53	-6	0	+47
GP2.5	+49	-4	0	+45
GP5 M*	+55	-6	0	+49
GP7.5 M*	+56	-5	0	+51
GP10 M*	+50	-5	0	+45

insulation thickness generally leads to a neutral or slightly beneficial effect in terms of the total number of heat stress events.

Tables 5.8 and 5.9 report all the data in detail, allowing a clearer understanding of the order of magnitude of the number of events considered. Overall, both configurations (14.5 cm and 7 cm) correspond to more than 16 hours of heat stress over the analysed period.

Overall, the results indicate that the effectiveness of the insulation thickness depends on the type of thermal stress considered. While higher thickness improves resistance to more severe conditions, lower thickness enhances the dynamic response of the building, resulting in a more favourable overall performance under the analysed summer scenario.

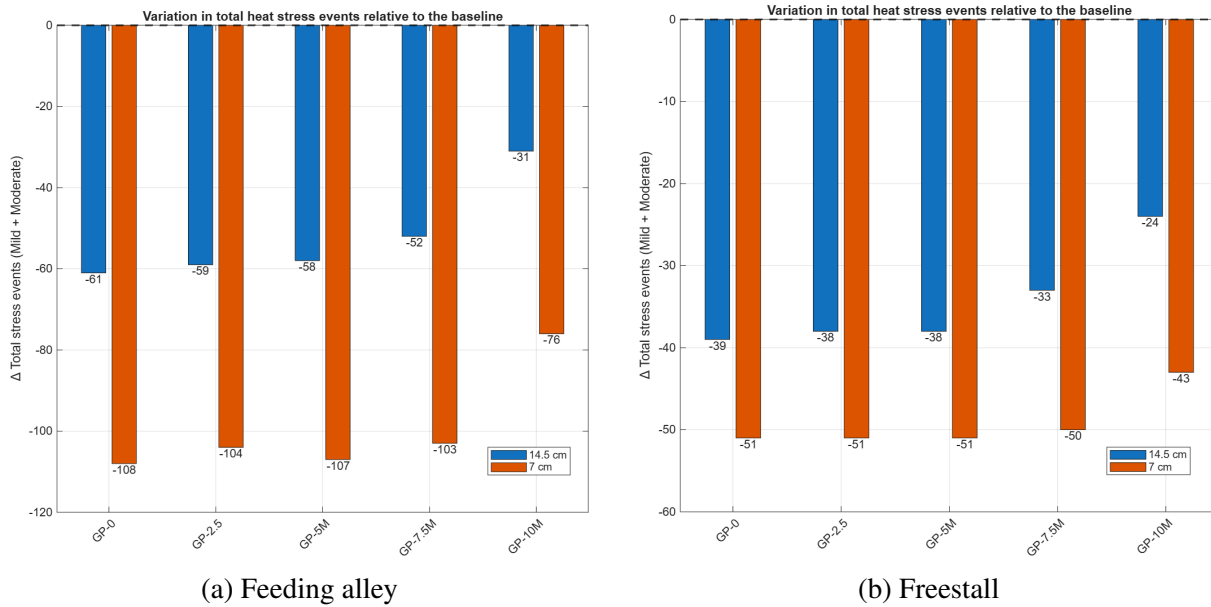


Figure 5.9: Total number of heat stress events (mild + moderate) for the analysed configurations in feeding alley and freestall

Table 5.7: Difference in the number of heat stress events between configurations with thickness of 14.5 cm and 7 cm in the freestall area

Configuration	Δ Mild	Δ Moderate	Δ Severe	Δ Total
GP0	+26	-14	0	+12
GP2.5	+29	-16	0	+13
GP5 M*	+29	-16	0	0
GP7.5 M*	+33	-16	0	0
GP10 M*	+33	-14	0	0

Table 5.8: Comparison of heat stress events in the feeding alley for different configurations and material thicknesses

Structure	$72 \leq \text{THI} \leq 79$	$79 < \text{THI} \leq 90$	$\text{THI} \geq 90$	Total
Normal Wall	3734	1128	0	4862
P800	3655	1135	0	4790
Only GP0 (14.5 cm)	3686	1115	0	4801
Only GP2.5 (14.5 cm)	3689	1114	0	4803
Only GP5 M* (14.5 cm)	3689	1115	0	4804
Only GP7.5 M* (14.5 cm)	3696	1114	0	4810
Only GP10 M* (14.5 cm)	3716	1115	0	4831
Only GP0 (7 cm)	3633	1121	0	4754
Only GP2.5 (7 cm)	3640	1118	0	4758
Only GP5 M* (7 cm)	3634	1121	0	4755
Only GP7.5 M* (7 cm)	3640	1119	0	4759
Only GP10 M* (7 cm)	3666	1120	0	4786

Table 5.9: Comparison of heat stress events in the freestall area for different configurations and material thicknesses

Structure	$72 \leq \text{THI} \leq 79$	$79 < \text{THI} \leq 90$	$\text{THI} \geq 90$	Total
Normal Wall	3714	1515	0	5229
P800	3664	1524	0	5188
Only GP0 (14.5 cm)	3697	1493	0	5190
Only GP2.5 (14.5 cm)	3699	1492	0	5191
Only GP5 M* (14.5 cm)	3697	1494	0	5191
Only GP7.5 M* (14.5 cm)	3702	1494	0	5196
Only GP10 M* (14.5 cm)	3711	1494	0	5212
Only GP0 (7 cm)	3671	1507	0	5178
Only GP2.5 (7 cm)	3670	1508	0	5178
Only GP5 M* (7 cm)	3668	1510	0	5191
Only GP7.5 M* (7 cm)	3669	1510	0	5196
Only GP10 M* (7 cm)	3678	1508	0	5212

Chapter 6

Conclusion and consideration

The aim of this work was to evaluate the potential of a bio-based material derived from grape pomace, applied to the building envelope of a dairy barn, in order to mitigate heat stress in cattle. In addition, the study assessed the feasibility of using a locally available by-product to reduce both construction costs and environmental impact.

To achieve this objective, a detailed model of the barn was developed, based on both on-site measurements and building information provided by the farmer. The monitoring campaign allowed the collection of air temperature, relative humidity, and CO₂ concentration data, which were used to assess animal welfare through the THI index. These measurements were also used to identify distinct thermal zones within the barn, enabling a more accurate representation of the building in the simulation model. Once a satisfactory agreement between the model and the measured data was achieved, the model was implemented in TRNSYS (Type 56) and coupled with CONTAM (Type 97) to account for airflow and ventilation effects. The calibration process showed good agreement between simulated and measured data, allowing further parametric analyses.

Different configurations were simulated by varying both the composition and thickness of the bio-based material. The analysed materials included five different concentrations of grape pomace (0%, 2.5%, 5%, 7.5%, and 10% by weight). Additional simulations were performed by adjusting the heat capacity of selected configurations, adopting an average value of 0.9 kJ/(kg K).

The winter analysis confirmed that heat stress is negligible in cold conditions, as expected, thus providing an additional validation of the model. On the contrary, the summer simulations highlighted critical conditions, even in a mountain environment.

The results indicate that the addition of the bio-based material slightly modifies the thermal behaviour of the barn. In general, a reduction in the number of heat stress events was observed, although the effect remains limited. The freestall area was identified as the most critical zone, due to the prolonged presence of animals.

Among all the analysed configurations, the structure combining the P800 wall with an additional layer of GP at 7.5% shows the best performance in terms of reduction of total heat stress events. Under summer conditions, considering the three hottest weeks of 2025 (from June 13th to July 3rd), the baseline scenario exhibits heat stress for 17 out of 21 days. In this context, the proposed configuration leads to a reduction of heat stress exposure of approximately 8 hours in the freestall area and about 4 hours in the feeding alley. A more detailed analysis shows that this improvement is mainly associated with the mild heat stress range ($72 \leq \text{THI} \leq 79$), where

a significant reduction in the number of events is observed. In contrast, for moderate heat stress conditions ($79 < \text{THI} \leq 90$), the performance is comparable to that of the reference configuration. These results highlight that the proposed material can represent a viable alternative to the insulation currently used in the barn, contributing to an overall reduction in heat stress conditions.

A key outcome of this study is the role of material properties and thickness. The results show that reducing the thickness decreases the number of mild heat stress events but increases moderate ones. For instance, in the feeding alley, under moderate heat stress conditions, the 14.5 cm configuration leads to a reduction of approximately 1 hour of stress compared to thinner solutions. Conversely, under mild heat stress conditions, the 7 cm configuration results in a reduction of about 8 hours. Overall, when considering the combined effect of mild and moderate heat stress, the configuration with lower thickness leads to a lower total number of negative events in both the freestall and the feeding alley compared to the thicker configuration. This behaviour can be explained by the interaction between thermal conductivity and volumetric heat capacity. While lower thermal conductivity improves insulation, a reduction in volumetric heat capacity limits the ability of the structure to absorb and delay heat gains. Therefore, the thermal inertia of the envelope plays a crucial role in determining indoor conditions. As a result, under the analysed summer conditions, a bio-based material with reduced thickness appears to provide a more favourable overall performance compared to thicker solutions. However, it should be noted that the differences between configurations remain relatively small, with variations corresponding to only a few events. Therefore, the selection of the optimal configuration is not straightforward, as several solutions exhibit comparable performance.

It is also important to consider that a significant portion of heat is internally generated by the animals. In the absence of effective ventilation, heat dissipation is limited, further worsening indoor conditions.

The analysed barn represents a specific case study, characterized by a relatively closed structure and relying solely on natural ventilation. Therefore, the results cannot be directly generalised to typical barns in the Po Valley, where open structures and mechanical ventilation systems are more commonly adopted.

In conclusion, the proposed bio-based material represents a potentially sustainable alternative to conventional insulation materials. However, its effectiveness in reducing heat stress is limited and strongly dependent on its thermophysical properties and application. Further investigations are required to evaluate its performance in different climatic conditions and building configurations, as well as its economic feasibility in terms of production and maintenance costs.

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Acronyms

ABPs Agricultural By-Products. 1, 11

GP Grape pomace. 1, 20, 21, 74, 91

HS Heat Stress. 14

LW Longwave radiation. 16

NRC National Research Council. 18

THI Temperature Humidity Index. 1, 12, 17–19, 22, 66, 67, 71, 73, 74

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