

**HAROLD ARLEY TORRES CORDERO**

**Computational fluid dynamics modeling of thermal parameters and airflows  
and design improvement of naturally ventilated swine facilities in tropical  
climates**

Dissertation submitted to the Agricultural Engineering Graduate Program of the Federal University of Viçosa in partial fulfillment of the requirements for the degree of *Magister Scientiae*.

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*To God and to my parents.*

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To God.

To my parents for believing in me, help me in this stage of my life, especially in the most complicated moments.

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*“Derrotados son solo aquellos que bajan los brazos y se entregan”*

(Pepe Mujica)

*“Si buscas resultados diferentes, no hagas siempre lo mismo”*

(Albert Einstein)

*“Discipline sooner or later will defeat intelligence.”*

(Yokoi Kenji Díaz)

*“O único lugar aonde o sucesso vem antes do trabalho é no dicionário”.*

(Albert Einstein)

## ABSTRACT

TORRES CORDERO, HAROLD ARLEY, M.Sc., Federal University of Viçosa, march, 2023. **Computational fluid dynamics modeling of thermal parameters and airflows and design improvement of naturally ventilated swine facilities in tropical climates**. Adviser: Ilda de Fatima Ferreira Tinôco. Co-advisers: Veronica Gonzalez Cadavid, Jairo Alexander Osorio Saraz, Robinson Osorio Hernandez.

Mathematical techniques, such as Computational Fluid Dynamics (CFD), are being increasingly applied as a basis for designing facilities for animal production, as well as for guidance on the respective ambience. As a result, economy and speed have been achieved in the choice and design of construction typologies, as well as improvements in decision-making related to the well-being of animals and workers throughout the production chain. However, studies on the use of CFD for modeling processes in traditional pork production in regions with tropical and subtropical climates, such as Brazil and Colombia, are still limited. The objective of this investigation was to evaluate thermal comfort and air flow in three different types of pig housing construction, typical of Colombia, naturally ventilated and with different thermal floors (cold, mild, and warm), used in the fattening phase. Then, the objective was to propose improvement of the thermal conditions in the environment of those facilities, based on the Temperature and Humidity Index (THI). The three typical facilities used were selected from a set of ten covered in a previous study. In the present study, pigs at the beginning of the fattening phase, with an average of 70 kg of body weight, were used. To validate the information related to the thermal environment, air temperature (T), relative humidity (RH) and air velocity (v) data were collected at different points, uniformly distributed inside each of the different facilities. For this, a low-cost sensor, specifically developed for the study. CFD was used to model and simulate the variation of such parameters for different typologies. After that, a comparison was made with the field data, verifying the correspondence between them, based on the Normalized Mean Squared Error (NMSE), used to validate the information obtained by the simulation. For the typologies of pig facilities with the worst average conditions (THI below 74), improvements in hygrometric and thermal conditions were proposed, via simulation of the application of a ventilation system associated with an evaporative cooling system. It was verified that, with this study, it was possible to validate the modeling conducted via CFD, observing statistically acceptable values of the modeled parameters, thermal

and air flow, in comparison with those obtained in the field conditions. Alternative ventilation and evaporative cooling systems were proposed for two of the analyzed production facilities, in which it was possible to reduce more than 4.8°C in temperature and add more than 0.40 m/s in air flow, in both cases. As a result, there was a reduction in the triggering of comfort alarms in these pork production units.

Keywords: simulation, mathematical techniques, rural constructions, pig Facilitying, animal ambience, ventilation.

## RESUMO

TORRES CORDERO, HAROLD ARLEY, M.Sc., Universidade Federal de Viçosa, março, 2023. **Modelagem por dinâmica computacional de fluidos de parâmetros térmicos e de fluxos de ar e melhoria projetual de instalações de suínos naturalmente ventiladas em climas tropicais.** Orientador: Ilda de Fatima Ferreira Tinôco. Coorientadores: Veronica Gonzalez Cadavid, Jairo Alexander Osorio Saraz, Robinson Osorio Hernandez.

Técnicas matemáticas, tais como a Dinâmica de Fluidos Computacional (CFD), vêm sendo cada vez mais aplicadas como base para projetos de instalações para produção animal, bem como para orientação acerca da respectiva ambiência. Com isso, tem-se atingido economia e rapidez na escolha e concepção das tipologias das construções, bem como melhorias na tomada de decisão relacionadas ao bem-estar animal e dos trabalhadores de toda a cadeia produtiva. Contudo, ainda são restritos os estudos relativos ao emprego de CFD para modelagem de processos na produção tradicional de suínos em regiões de climas tropicais e subtropicais, a exemplo do Brasil e da Colômbia. O objetivo desta investigação foi avaliar o conforto térmico e o fluxo de ar em três diferentes tipologias construtivas de alojamentos de suínos, típicas da Colômbia, naturalmente ventiladas e com distintos pisos térmicos (frio, temperado e quente), utilizadas na fase de terminação. Em seguida, objetivou-se propor melhoria das condições térmicas no ambiente daquelas instalações, com base no Índice de Temperatura e Umidade (THI). As três instalações típicas utilizadas foram selecionadas de um conjunto de dez abordadas em um estudo anterior. No presente estudo foram utilizados suínos em início da fase de engorda, com 70kg de peso corporal, em média. Para validar as informações relativas ao ambiente térmico, dados de Temperatura do ar (T), Umidade Relativa do ar (RH) e velocidade do ar (v), foram coletados em diferentes pontos, uniformemente distribuídos no interior de cada uma das diferentes instalações. Para isso, foi utilizado um sensor de baixo custo, especificamente desenvolvido para o estudo. CFD foi utilizada para modelar e simular a variação de tais parâmetros para as diferentes tipologias. Após isso, foi feita a comparação com os dados de campo, verificando-se a correspondência entre os mesmos, com base no Erro Quadrático Médio Normalizado (NMSE), utilizado para validar as informações obtidas pela simulação. Para as tipologias de instalações suinícolas com as piores condições médias (THI abaixo de 74), foram propostas melhorias das condições higrométricas e térmicas, via simulação de aplicação de

sistema de ventilação associado à sistema de resfriamento evaporativo. Verificou-se que, com este estudo, foi possível validar a modelagem realizada via CFD, observando-se valores dos parâmetros modelados, térmicos e de fluxo de ar, estatisticamente aceitáveis, em comparação com os obtidos nas condições de campo. Foram propostas alternativas de sistemas de ventilação e de resfriamento evaporativo para duas das instalações de produção analisadas, nas quais se conseguiu reduzir mais de 4.8°C na temperatura e acrescentar mais de 0,40m/s no fluxo de ar, em os ambos casos. Com isso, houve redução no acionamento de alarmes de conforto nessas unidades de produção de carne suína.

Palavras-chave: simulação, técnicas matemáticas, construções rurais, suinocultura, ambiência animal, ventilação.

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## LIST OF ACRONYMS AND ABBREVIATIONS

|           |  |
|-----------|--|
| AA        | Total number of pigs in each facility. |
| AO1       | Optimization 1 for Facility I.         |
| AO2       | Optimization 2 for Facility I.         |
| AO3       | Optimization 3 for Facility I.         |
| AO4       | Optimization 4 for Facility I.         |
| AOA       | Optimization A for Facility I.         |
| AOB       | Optimization B for Facility I.         |
| AW        | Average body Weight of pigs.           |
| BO1       | Optimization 1 for Facility II.        |
| BO2       | Optimization 2 for Facility II.        |
| BO3       | Optimization 3 for Facility II.        |
| BO4       | Optimization 4 for Facility II.        |
| BOA       | Optimization A for Facility II.        |
| BOB       | Optimization B for Facility II.        |
| BSA       | Body Superficial Area.                 |
| CF        | Cleaning frequency for facilities.     |
| CFD       | Computational Fluid Dynamics.          |
| DBF       | Distance between fans.                 |
| F1        | Breed of pigs.                         |
| RH        | Relative Humidity                      |
| MASL      | Meters above sea level.                |
| NMSE      | Normalized Mean Square Error.          |
| T         | Temperature.                           |
| THI       | Temperature and Humidity Index.        |
| v         | Air velocity.                          |
| $W_{pig}$ | Pig weight.                            |

## LIST OF SYMBOLS

|                 |  |
|-----------------|--|
| A               | Area   |
| $A'$            | Psychrometer constant.                                       |
| b               | Specific exponential constant for BSA equation.              |
| $E$             | Opening effectiveness.                                       |
| $e$             | Partial vapor pressure.                                      |
| $e_s$           | Saturation vapor pressure.                                   |
| $e_{su}$        | Saturation pressure at dry bulb temperature.                 |
| F               | Number of fans   |
| $f$             | Statistical valor to compare results of data groups.         |
| $f_{crit}$      | Statistical variable used to evaluate acceptable group data. |
| h               | hour.  |
| $hPa$           | Hect-pascal.   |
| K               | Kelvin degrees.  |
| kg              | kilograms.   |
| L               | thickness of material.                                       |
| m               | meters.  |
| $MS_{error}$    | Mean Square error within groups.                             |
| $MS_{Trat}$     | Mean Square between groups.                                  |
| $m^2$           | Square meters.   |
| $m^3$           | Cubic meters.  |
| $m'$            | Meeh constant for superficial area calculus.                 |
| $P$             | Atmospheric pressure.  |
| $p - value$     | measure the quality of the data collected.                   |
| Q               | Caudal   |
| $Q_{necessary}$ | Necessary caudal   |
| $Q_{tot}$       | Total caudal.  |
| $Q_{tot recom}$ | Total caudal recommended.                                    |
| s               | Second.  |
| $SS_{error}$    | sum of the squares of the error.                             |
| $SS_t$          | Total sum of squares.  |
| $SS_{trat}$     | Sum of the squares of the treatment.                         |
| SUM             | Sum of data.   |

|              |   |
|--------------|---|
| $t_{ab}$     | Dry air bulb temperature.                   |
| $T_{\alpha}$ | variable to compare means in Tukey testing. |
| U            | global heat transfer coefficient.           |
| W            | Watt.                                       |
| °C           | Celsius degrees.                            |
| %            | percentage.                                 |
| $\mu_n$      | Average of n group.                         |
| $\lambda$    | thermal conductivity.                       |
| $\Phi_{tot}$ | Total heat generated for pigs.              |

## SUMMARY

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## 1. INTRODUCTION

Pig farming has been gaining notoriety worldwide and increasing its value in several countries, emphasizing high production and consumption. World pork production in 2022 represented 34.8% of total meat production worldwide, with 125.6 million tons. Likewise, the pork meat market has increased its expansion, reaching 1.2%, although a little slower compared to the 4.5% obtained in 2021. The most representative countries in terms of expansion in pork production are China, Australia, Vietnam, Brazil. There are significant decreases in the use of land for pig farming in the United States, Canada, the Islamic Republic and Argentina (FAO, 2022).

International prices have had an upward trend since October 2020, as a consequence of the shortage of supplies from the main exporting countries of Asia and the Middle East (FAO, 2022). According to the information recorded by the Comunidad Profesional Porcina, (2022), China is the largest producer and importer of pork worldwide, the largest exporter of this product is the European Union. In terms of pork production, after China, the European Union is in second place, followed by the United States and Brazil is in fourth place.

Brazil stands out in the production of pork at the level of South America, being the largest producer and exporter of pork in this part of the continent (Embrapa, n.d.), participating with 4.4% of total world production and 1.3% of exports (Comunidad Profesional Porcina, 2022). The market in Brazil is growing, with a constant growth rate in production and increasing per capita consumption, also highlighting technological advances, good management and control of the production chain (Embrapa, n.d.).

Brazil, as a result of its great extension, has varieties of tropical and subtropical climates, and its geographical location close to the equator makes high temperatures very common, easily exceeding 25 degrees Celsius. These high temperatures are more frequent in the summer season and if they are not controlled, they would be responsible for economic losses (Valverde et al., 2023). Uncontrolled increases in temperatures in productive environments cause a decrease in food intake and less weight gain in animals, since they can reach heat stress (Valverde et al., 2023).

Colombia is another example where pigs are at risk of heat stress in production in the same way. The most recent FINAGRO report (2020) highlights that Colombia produced close to 447,000 tons of pork, although it barely participates with 0.13% of world production, data obtained in 2020 (FAO, 2020). Colombia has approximately 233 facilities for production and the participation of 56 pork processing facilities, among the main producing states are: Antioquia, Cundinamarca, Valle and Meta, with Antioquia being the main producer, value verified for the year 2019. The main breeds used in Colombian production are Landrace, Large White, Hampshire, Duroc and Pietrain (FINAGRO, 2020). In 2020, pork production increased 5% compared to 2019, representing a development of agribusiness in Colombia. On the other hand, Porkolombia, (2023), provides information on the production of pork in Colombia, revealing that by the year 2022 production has doubled compared to the historical information of the last ten years, showing the importance of continue to improve this sector.

When considering the National Livestock Census, Colombian Pig Farming generates more than 135,000 jobs, with a total of 6.7 million head of pig (FINAGRO, 2020). In a census carried out in 2018 by Piñero & Montalvo, (2018), they mentioned that of the total farms surveyed that have the capacity to raise pigs, 27% are considered technical farms, with inventories of pigs, complete production cycle with 10 or more females and 40 or more pigs in the fattening phase. FINAGRO, (2020), clarifies that by the year 2020, 61% of the total national production is in technical environments, the remaining 39% belongs to traditional production. Comparing the two studies mentioned, it can be said that there has been an increase in the modernization of pig farms in recent years, and these are concentrated in the states of Antioquia, Valle del Cauca and Cundinamarca (Piñero & Montalvo, 2018).

Currently, the management and handling of pig production systems is divided according to the physiological phase in which the animal is, since different needs are met in each phase (Piñero & Montalvo, 2018). Each productive system has a section for the reproducers, which are selected according to genetics and behavior, they transmit to their offspring the desired characteristics to improve production, meeting market demands, they have a weight of 130 to 150 kilograms and between 7.5 and 8 months. The second section is that of replacement and replacement females, which are genetically selected, in the future they will be farmed breeding mothers, they are approximately seven months old with a weight between 130 and 150 kilograms. Pregnant females is the third section, this process lasts between 114 and 115 days. The next section are lactating females, where they remain for an average of 25 days, and the piglets are found in the same way from the time they are born until they reach a weight of between 6 and 7 kilograms (Piñero & Montalvo, 2018).

There is another section where the empty females that have already finished lactation or that pregnancy was not effective are found. This period is considered non-productive and can last between 6 to 8 days. Discarded females are those that have completed their production process and are destined for slaughter. The pre-baited piglets finished their lactation process and are separated from the rest until they reach a weight of 30 kilograms. This process can last up to 49 days, where they go to the rearing section. The rearing section has special nutritional management and can last from 6 to 8 weeks, until the pigs reach a weight between 50 and 60 kilograms. In the fattening or finishing phase, the pigs reach their final weight between 110 to 125 kilograms, conditioned by market demands, the entire process from birth can last from 168 to 180 days (Piñero & Montalvo, 2018).

Producers have the availability to choose, according to their needs, a series of production systems for raising pigs, among which are continuous flow farms, where animals enter and leave different areas according to their physiological phase, in some cases they are in the same facility, in others they must be transferred to another building. Another system used is all-in – all-out management (TD-TF) are small sections in a single house properly separated to avoid contact, the animals enter and leave the pens according to the schedule. The farms in one site have all the physiological stages in the same place, and the farms with two and three sites have specialized pens for certain physiological stages of the pig, duly separated (Piñero & Montalvo, 2018). Different types of materials are used in the constructions, concrete can be used for floors, grooved floor on washable floor, grooved floor on floodable pit and deep bed used with pigs in the rearing phase (Piñero & Montalvo, 2018).

In Colombia, land-related activities, such as agriculture, generate 43% of total greenhouse gas emissions, 8% of waste, and 44% of energy (Castrillón et al., 2020). Activities related to livestock farms are directly related to the generation of manure and pig manure, in and of themselves these products do not initially contain high-risk compounds, but large volumes can cause problems when managing them (Piñero & Montalvo, 2018). Despite the fact that they are washed inside the facilities, the mixture of water with substances derived from swine production, these products do not change their agronomic and environmental characteristics, so they must be catalogued, separated and treated like any organic compound (Piñero & Montalvo, 2018).

Environmental impacts can be mitigated by intensifying specialized lines of animals under controlled conditions that can generate gases, among those abundant greenhouse gases such as methane ( $CH_4$ ) and carbon dioxide ( $CO_2$ ) (Simões et al., 2021). Environmental effects can appear when eliminating the waste generated by pigs, these effects are characterized by having a high content of organic matter, high content of macronutrients (Nitrogen, Phosphorus and Potassium), some micronutrients, and generating easily volatilizable compounds such as methane gas, ammonia and nitrous oxide (Piñero & Montalvo, 2018).

Considering the environmental effects generated in pig production, field techniques must be carried out to avoid contamination of bodies of water, eutrophication of surface waters, acidification produced by ammonia, as well as having as a variable the contribution effect of daily activities in the greenhouse gas facilities and bad odor problems (Piñero & Montalvo, 2018). Once the problem is known in general, points must be identified where there is a greater risk of pollutant emission (Piñero & Montalvo, 2018).

External and internal environmental conditions have different effects on the facilities, they can be classified as direct and indirect. Temperatures outside the thermal comfort zone lead to a reduction in productivity and generate economic damage (Damasceno et al., 2019). There are indicators of thermal stress that are measured within livestock facilities, they are indices that quantitatively show the comfort state of the animals (Osorio et al., 2021). There are studies focused on the use of biomass as energy in swine production in Colombia (Amado, 2021), animal welfare (Cables et al., 2022), diseases such as swine fever (Abuín et al., 2021).

In order to mitigate the environmental effects, the following points should be considered: delimit the location of production and environmental planning. The waste management place must have a distance from protected places such as forests and bodies of water to avoid mass contamination, the activity must be duly distanced from areas of human settlements, raw material supply areas and transportation routes of inputs and outputs. On the other hand, it is important to know the local environmental regulations and have trained personnel for environmental control and management (Piñero & Montalvo, 2018).

Some strategies are recommended to reduce environmental impacts in pork production. Efficient use of water must be made by scheduling cleaning activities, control of the use of water for consumption and washing. Another measure is energy management, the use of available spaces must be optimized, establishing the

appropriate animal density, adjusting the temperature and ventilation control systems, thermally insulating the sheds, performing electrical equipment maintenance, registering energy consumption (Piñero & Montalvo, 2018). Energy consumption is very demanding in summer and winter, an energy efficient ventilation system combined with a pad fan evaporative cooling process is essential for sow growth and production (Li et al., 2020). There are few recent studies on energy use in swine production facilities. The next strategy is feeding, it is important to maintain an adequate nutritional management of the animals and the application system, adjusting the animal's requirements, with a balanced diet, improving the absorption of nutrients. This can reduce the generation of unwanted waste (Piñero & Montalvo, 2018).

Control of the indoor environment is of great importance, good ventilation favors the exchange of air with the outside, preventing gases such as ammonia from concentrating, attending to and adjusting to the thermal needs of the animals generates well-being for the pigs, maintaining yields productive (Piñero & Montalvo, 2018). Later, solid waste management must be stored on a permeable surface where leachate is collected, allowing air flow to prevent water entry, storage capacity must be designed according to the size of the production system. Liquid waste can be collected and stored in tanks, designing its storage capacity for proper handling and subsequent use as fertilizer, avoiding contamination of bodies of water. The objective of waste management is to reduce nitrogen and phosphorous emissions into the environment, there are mechanical, physicochemical, panel evaporation and biological separation systems (Piñero & Montalvo, 2018).

Other very important biological wastes are corpses and fetuses, they must be disposed of in a specific place, as an option there is composting where organic matter decomposes, reducing biological risks. Within the facilities, waste is separated and treated in a specific place for storage in suitable containers (Piñero & Montalvo, 2018).

Considering animal welfare in production leads to a series of practices that have been spreading more and more over time. Considering animal welfare as a physiological state, it can be measured and evaluated in order to determine its causes and the strategies to keep it within an adequate range. Welfare Quality® defined 4 principles for animal welfare: feeding, housing, health and behavior. These principles can be subdivided, to maintain a good diet there should be no prolonged hunger or thirst, good accommodation talks about rest comfort, thermal comfort and ease of movement, good health considers avoiding injuries, illnesses, and induced pain by management procedures, in last place, the behavior that promotes the expression of social behavior, good human-animal relationship and avoidance of fear is considered (Ghezzi, 2018).

The demand for food has been forcing producers to optimize their processes with the use of technologies, there is a tendency to increase production efficiency, health using technological tools such as sensors (cameras, microphones, accelerometers, radio frequency identification transponders), combined with mathematical algorithms. The information obtained is a high-potential herd management strategy that allows the detection of diseases, improves well-being and increases the productivity of the offspring (Racewicz, 2021).

The aforementioned variables can be measured quantitatively, if comfort increases, the overall score increases. The principles of animal welfare can be divided into five

types: physical, physiological, behavioral, productive and health (Ghezzi, 2018). Different measurements are made with the use of instrumentation to determine comfort, they are also used to determine diseases in animals. There are two types of measures used for the diagnosis of comfort and diseases, invasive tests that involve the contact of the instruments with the animal (Wayne, 2022) and non-invasive tests with the absence of contact.

With the aim of optimizing practices related to animal welfare, a series of techniques and instruments are used to help in this important aspect of production. It is important to plan the nutritional management in each of the physiological stages of the pig (Piñero & Montalvo, 2018), use instruments to measure the thermal environment and the temperature of the animal, there are invasive ones to measure body temperature such as thermometers, non-invasive ones such as datalogger that collect information on temperature, relative humidity and air quality. The use of thermographic cameras is a promising technique that measures the surface temperature distribution of objects using infrared thermography, allowing it to be controlled and in many cases replaced invasive measures (Comunidad Profesional Porcina, 2013).

It is possible to study the movements and activities carried out by the animals manually or with the use of hardware and software tools, allowing to know when the animals eat, sleep, interact socially, etc. The use of these monitoring systems through images is called early warning because they allow fast and accurate acquisition of data that support decision-making on farms, allows early detection of diseases, facilitates herd management, activates alarms and notifications (Racewicz et al., 2021). By reviewing the productive environment, injuries can be reduced, by reviewing the history of the farm, diseases can be found and treated (Wayne, 2022).

Among the tools to monitor the production environment, the use of mathematical techniques has great potential for use because they are non-invasive methods for animals, preventing them from becoming stressed by contact with measuring instruments. These systems can provide very precise approximations that will allow an improvement in decision-making for the control of environmental conditions, to guarantee the well-being and comfort of the animals. One of these techniques is Computational Fluid Dynamics (CFD) which models and simulates the interactions between the environment and animals. Many studies with CFD have been developed for agriculture, these consider the flow fields and the interaction between the heat production of animals and the ventilation of commercial facilities, considering realistic models and surrounding facilities (Gautam et al., 2021).

The use of CFD in agriculture has been a representative tool used to develop technologies and improve different processes. CFD has been used in the use of alternative energies to mitigate the effects of climate change (Williams et al., 2023), solar drying systems applied to dairy processing (Qamar, et al., 2023), solar greenhouses with natural ventilation to study the behavior of temperature and airflow (Fu et al., 2023). A large number of studies have been published recently, in aquaculture CFD was used to study the behavior of fish (Liu et al., 2023) as well as to study the air flow inside factories where products are stored (Natarajan, 2022).

By 2050, the world population is expected to be 9.5 billion people (Simões et al., 2021). Currently, agriculture and industry are increasing their efforts to meet the

demand for products, including meat, which are increasing due to the aforementioned increase in the population and the standard of living in many sectors (Hernández & Martín, 2020). Animal production must guarantee the highest quality standards aligned with global requirements (Martínez et al., 2022). Consumers demand products with a lower environmental footprint, and for this, pig producers are responsible for reducing the environmental effects of their products, however, they need to know the benefits their practices can incorporate (Tallaksen et al., 2020).

In general terms, to produce meat at a commercial and industrial level, it is important to consider the thermal environment and air quality to guarantee the health of animals and workers. Researchers around the world develop studies that consider the temperature, relative humidity, air velocity, and gas concentration within the facility to perform a systematic evaluation (Wang et al., 2021). Simulations in the CFD must consider animals and partitions to identify regions of interest in terms of ventilation conditions within the facility (Gautam et al., 2021). CFD is an alternative successfully adopted in many studies (Wang et al., 2021), which can contribute to reducing the environmental footprint within intensive production systems and thus improve the development and use of non-invasive technologies in pig production.

CFD shows that its results are a predictive method that can reduce costs and time in future projects focused on agriculture in different parts of the world. In addition, CFD helps to improve the efficient use of energy, reducing errors in the execution of projects, contributing to the reduction of food losses and guaranteeing a better environment for production. Additionally, Colombia aims to improve production efficiency, increase the acceptance and consumption of pork, strengthen sanitary conditions, provide producers with modernization tools, considering animal welfare and using innovative technologies (Díez, 2022).

## **2. OBJECTIVES**

### **GENERAL OBJECTIVE**

Evaluate the thermal environment and air flow of different traditional facilities of pigs naturally ventilated in tropical climate based on CFD simulation.

### **SPECIFIC OBJECTIVES**

Validate three typological constructive facilities according to thermal and humidity index and air flow obtained previously to which pigs are exposed in intensive production systems with different thermal floors, located in tropical climate using CFD technics.

Propose improvement of selected facilities based on the conditions of not comfort and air flow reviewed as an individual production system, considering ventilation and thermal conditioning systems using computer simulation.

## **3. MATERIAL AND METHODS**

### **3.1. Selection of facilities**

This evaluation was carried out in intensive pig production units, located in the state of Antioquia - Colombia, these types of facilities are considered traditional or typical in the region, additionally they are open and have natural ventilation, the distribution of spaces was different in the three cases studied. The cleaning

frequency (CF) in the facilities is 1 daily and 2 every two days, when the facility is completely evacuated.

The facilities have smooth concrete floors. The classification in thermal floors shows the reality of pork production in Colombia. It was necessary to consider certain properties of the materials used in the construction, this as input data in simulation (Table 1). The variables considered to select three facilities are initially MASL, Thermal Floor Classification and Temperature and Humidity Index (THI) applied for the comfort of the animals inside the building.

Table 1. Thermal conductivity, thickness, and heat transfer coefficient of materials were used in ceiling and walls in this study. Font (Sun, 2016).

| Variable                           | concrete slab | zinc tile | asbestos |              | clay tile |
|------------------------------------|---------------|-----------|----------|--------------|-----------|
|                                    |               |           | cement   | Masonry wall |           |
| <b>Thermal conductivity</b>        |               | 1.13E+0   |          |              |           |
| $\lambda$ [W/m*K]                  | 2.00E-01      | 2         | 3.00E-01 | 6.45E-01     | 1.21E-01  |
| <b>thickness L [m]</b>             | 2.50E-01      | 2.00E-04  | 5.00E-03 | 2.30E-01     | 8.00E-02  |
| <b>Heat transfer coefficient U</b> |               | 5.65E+0   |          | 2.80E+0      | 1.51E+0   |
| [W/m <sup>2</sup> *K]              | 8.00E-01      | 5         | 6.00E+01 | 0            | 0         |

For this investigation, environmental and airflow information was used. The characteristics of the mountainous relief of Antioquia, the climatic variants and the thermal floors were considered. The temperature (T), relative humidity (RH) and air velocity ( $v$ ) data were evaluated. A total of 3 facilities were selected, each one on a different thermal floor. Facility I is located between 0 to 1000 MASL considered in a warm thermal floor, between 1000 and 2000 MASL Facility II was selected in a warm thermal floor, and Facility III was between 2000 and 3000 MASL in a cold thermal floor.

These types of structures were selected from a total of 10 from a previous study carried out by (Osorio et al., 2021), where the structures were characterized and the general condition of each one could be known, in terms of comfort and air flow. Facility I had the worst comfort score measured with THI among structures with the same thermal floor. For Facility II, a wide range of temperature distribution was found, showing very high and low THI values, and a low air renewal rate. Facility III had the worst THI score among farms on the same thermal floor.

Facility I uses curtains to control internal environmental conditions, it does not have side walls for ventilation. Facility II uses semi-sided walls and curtains and Facility III features small windows with side curtains. There are no mechanical control mechanisms for the environment in the facilities. Table 2 shows the heat flow classification, MASL, some characteristics, THI classification and number of pigs (AA) per facility, according to the results obtained by Osorio et al., (2021).

The information was collected between July and August 2019 in a dry summer period. Historical weather conditions between July and August in Antioquia show a dry period with low rainfall, in a climate considered warm (Clima y clima promedio todo el año en Antioquia, n.d.). Facility I is the largest facility, but,

according to Table 4, it has the lowest height above sea level and has the highest temperature conditions.

Table 2. Thermal floor, THI, MASL, pigs per facility and pig density for the three facilities. Font (Castrillón et al., 2021).

| Facility | Thermal floor | THI assessment    | MASL | Pigs per facility | Pig density [m <sup>2</sup> /pig] |
|----------|---------------|-------------------|------|-------------------|-----------------------------------|
| I        | Warm          | Discomfort        | 816  | 29                | 15.15                             |
| II       | Mild          | Dangerous Thermal | 1408 | 34                | 17.65                             |
| III      | Cold          | comfort           | 2202 | 23                | 4.71                              |

Facility II is the second largest, has the worst comfort ratings of the three facilities, and the highest number of pigs. Facility III is the smallest of all and has the highest density of animals. Some dimensions and construction properties used mainly for modeling are shown in Table 3. Facility III has the fewest number of pigs and the best comfort rating. Facility II has the largest airflow inlet, Facility I has the largest window size. The three facilities have different roof materials (Table 4). Figure 1 shows which distances were used to measure the dimensions of the farms.

Baêta & Souza, 2010, mentioned the importance of knowing the pressure differences that are generated by the action of the wind on the structures. Considering these concepts and to better understand the behavior of the construction typologies, in an XY view the diagrams of the three installations were drawn, knowing previously the predominance of the wind and the shape of the installation. Pressure scheme is showed in Figure 2.

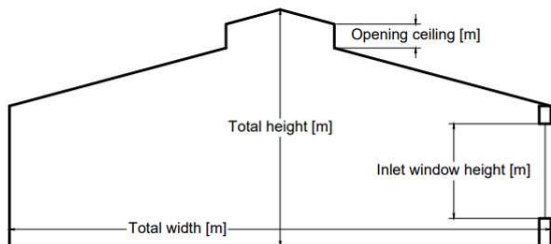
Table 3. Total length, width, build area, number of boxes, pigs per box and area per box for the three facilities. Font – author.

| Facility | X (Total length) [m] | Y (Total width) [m] | Build area [m <sup>2</sup> ] | Number of boxes | Pigs per box | Area per box [m <sup>2</sup> ] |
|----------|----------------------|---------------------|------------------------------|-----------------|--------------|--------------------------------|
| I        | 30.82                | 21.60               | 665.71                       | 20              | 2            | 30.29                          |
| II       | 63.60                | 11.35               | 721.86                       | 18              | 2            | 35.30                          |
| III      | 11.85                | 12.31               | 145.87                       | 6               | 4            | 26.20                          |

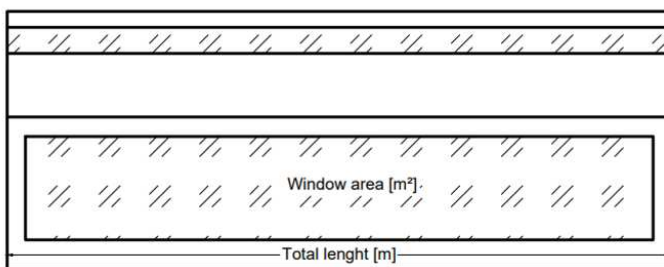
Table 4. Total height, inlet and opening area, and material of ceiling for three facilities for modeling. Font – author.

| Facility | Z (Total height) [m] | Inlet area [m <sup>2</sup> ] | Opening area [m <sup>2</sup> ] | Material of ceiling |
|----------|----------------------|------------------------------|--------------------------------|---------------------|
| I        | 5.33                 | 97.87                        | 185.48                         | Zinc tile           |

|     |      |        |        |                             |
|-----|------|--------|--------|-----------------------------|
| II  | 3.62 | 105.94 | 155.20 | Asbestos cement tile<br>5mm |
| III | 3.00 | 14.02  | 15.00  | Concrete slab               |



YZ view



XZ view

Figure 1. Dimensions and areas for facilities, taken for modeling, YZ and XZ view. Font - author.

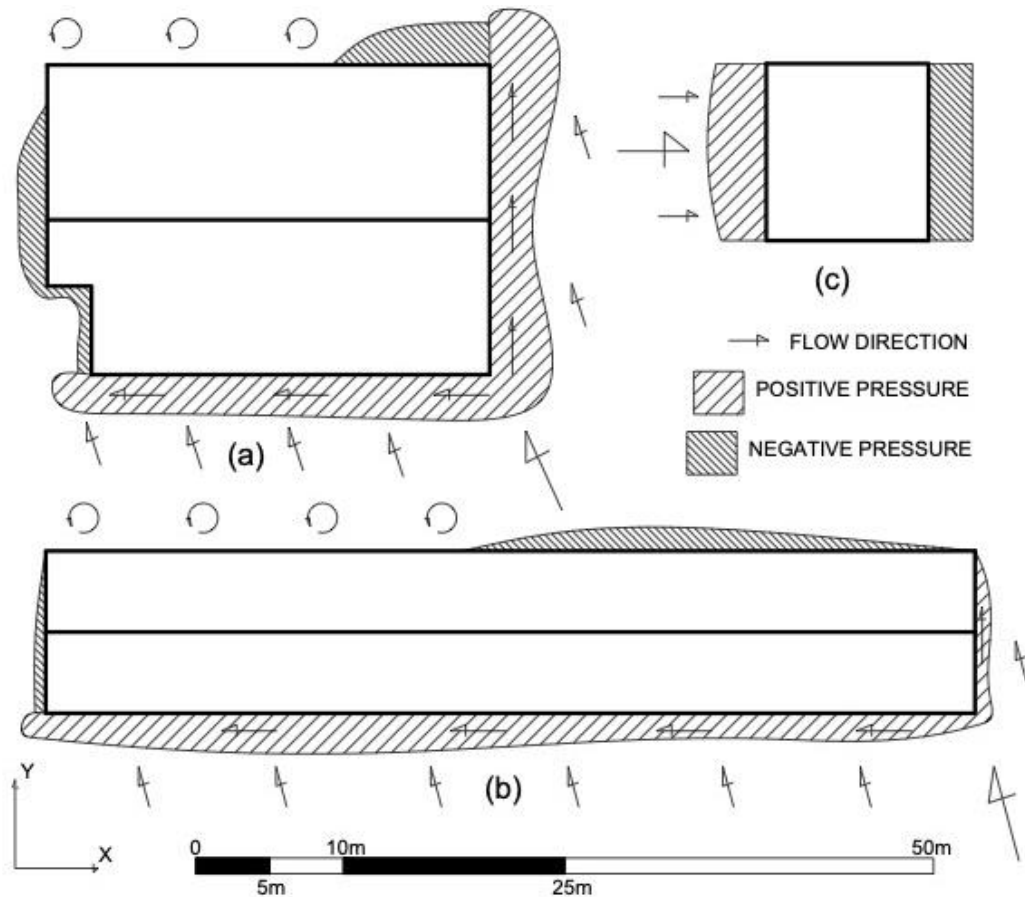


Figure 2. Pressure scheme on the sides of the facilities, XY view. (a) Facility I, (b) Facility II, (c) Facility III. Font - author.

### 3.2. Features of the experimental animals

The pigs of the facilities were in the fattening productive stage, 70kg of average weight (AW), between 9 to 15 weeks old, separated males from females, animal density was similar inside the facilities. The study objectives correspond to commercial pig fattening facilities. The animals come from crossing between the Landrace and Yorkshire breeds, known as F1 (first crossing between purebred). The study animals have the same nutritional management made by means of water and: 1) Energy sources such as corn, oils, fats, and agricultural by-products; 2) proteins of plant origin, which include soy and animal meal made from fish, meat, bones, and milk products; and 3) Vitamin and mineral supplements.

In order to understand the comfort state of the pigs, their heat emission was calculated, where the surface temperature measured in the previous study was taken (Osorio et al., 2021). Initially, the Body Surface Area (BSA) of pigs was determined using Equation 1, this calculation is known as the Meeh equation (Tadashi et al., 2017, p. 230). The total heat generated by the animal was calculated using the equation described by Pedersen & Sällvik, (2002) (Equation 2) used specifically for finishing pigs, based on internal environment temperature and food intake. Daily feed intake ( $n$ ) was considered as 3.15 for pigs weighing 70kg (Pedersen & Sällvik, 2002).

$$BSA = m' * (AW)^b \quad (1)$$

$$\Phi_{tot} = 5.09m^{0.75} + [1 - (0.47 - 0.003m)][5.09m^{0.75} * (n - 1)] \quad (2)$$

On that, BSA is in  $m^2$  for 70kg pigs it is  $1.2m^2$ ,  $m'$  is Meeh's constant for pigs is 0.0734 (Tadashi et al., 2017, p. 230),  $b$  is the exponential constant specific, for pigs is 0.0656, AW is the average weight of the pigs in kg,  $\Phi_{tot}$  is the total heat generated for the pigs in Watt, T is the temperature in °C,  $m$  is the weight of a pig in kg,  $n$  is the daily dietary energy intake.

### 3.3. Microclimatic instrumentation and data collection

A custom made low cost measurement system called Made Gas Measurement System (MGMS) was developed, they are sensor kit based on Arduino system where records are stored every 5 minutes on a microSD card, MGMS features are presented in Table 5 consigning the information on temperature, relative humidity and air speed with date and time.

Table 5. Low-cost sensor (LC) reference and measuring range for air temperature, relative humidity, and air speed.

| Sensor            | Reference         | Measuring range   |
|-------------------|-------------------|-------------------|
| Air temperature   | SHT31             | -40 - 60 °C       |
| Relative Humidity | SHT31             | 0 - 100%          |
| Air speed         | Wind sensor Rev P | 0 – 67 $m s^{-1}$ |

In this study, the Cartesian coordinate system X, Y and Z was used to represent each one of the models. In the data collection, the length and width of each installation (X and Y) were divided making a grid, in Figure 3 a representative example is shown in an XY view of a grid. The number of spaces varies according to the size of the module, leaving a space of at least 2 meters between points, at a height Z of 1.2 m (Osorio et al., 2021).

The measured data was taken from a data cloud where it began at 6:00 a.m. and ended at 6:00 p.m. at 3-hour intervals for each facility for 3 days, the information collected at 3:00 p.m. was used, where the highest THI values were reached. Four sensor kits distributed in each facility were used, in the same way the predominance of the wind direction was determined, evidencing air inlets and outlets. The surface temperature of the animals was determined with the use of a thermographic camera, being part of the previous study carried out by Osorio et al., (2021), additionally an architectural survey of each facility was carried out to know the dimensions, distribution of beds and building spaces and materials.

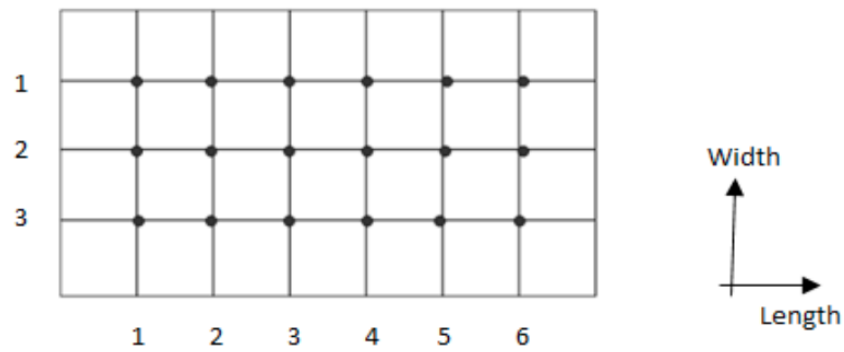


Figure 3. Scheme of grid for distribution of points where the information was taken by sensor-kits in the facilities, XY view. Font (Osorio et al., 2021)

### 3.4. Facility and animal modeling

The modeling was developed in software specifically designed for this purpose, based on finite volumes. In these models, volumes composed of surfaces that are associated with defined boundary conditions are drawn. Climatic variables (outdoor temperature, pressure, air speed and direction that passes through surfaces) and thermal properties of the materials (Table 1) are part of the input variables considered in the models. The models approximate reality, they consider the most representative parts of the facilities, they are differentiated in the model and the windows, doors, walls, ceilings and floors are mainly distinguished. Each surface has a defined direction of flow so that the simulation software can perform calculations, for this reason a vector analysis is performed, shown in Figure 4.

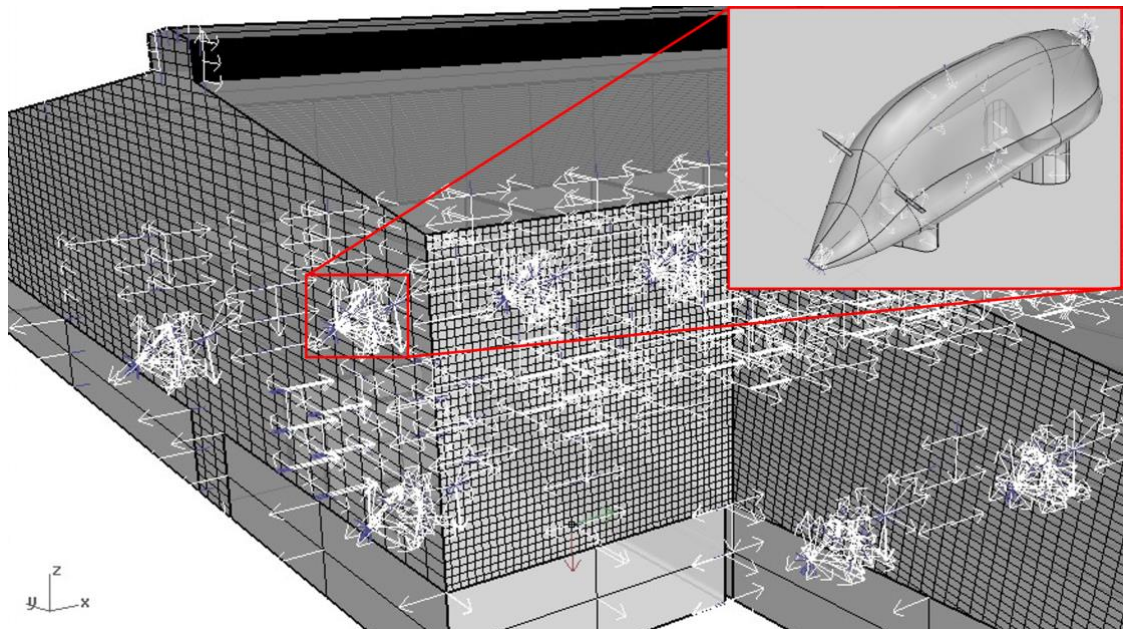


Figure 4. Vector revision in modeling for structure and pigs. Font – the author.

For animal modeling, a series of 5 geometries were initially evaluated to select the best option in terms of approximation to reality and ease of calculations through software, each model complies with the BSA calculated with Equation 1. The With the same boundary conditions for comparison, the pig models were

placed inside a cube 2m long on each of its sides, a representative model inside a cube is shown in Figure 5.

The relevant variables of each constructive typology and of the animals to be modeled are the geometric shape (length, width and height of the facilities, distribution and number of beds, type of roof, constructed area), type of ventilation (wind direction, measurements and areas of entry and opening of air windows), construction materials (wall thickness, thermal properties) and the characteristics of the animals (total number of animals in each facility (AA), pigs per litter, dimensions and surface areas of pigs, Average weight of pigs (AW) in kg).

The vector review modeling process is considered as a single object, which process ends with a CFD verification where problems are corrected (multiple edges, triangular boxes, single edges, non-multiple vertices and non-connected vertices) guaranteeing the quality of the modeling process. model and that there are no possible errors (duplicate elements, uncovered faces, find missing internal faces, volume orientations, surface orientations, dangling elements). Subsequently, the models of the facilities must go through a meshing process, in this step it is necessary to create a subdivision of the surfaces in the facility (doors, windows, walls, ceiling, animals, floor and windows).

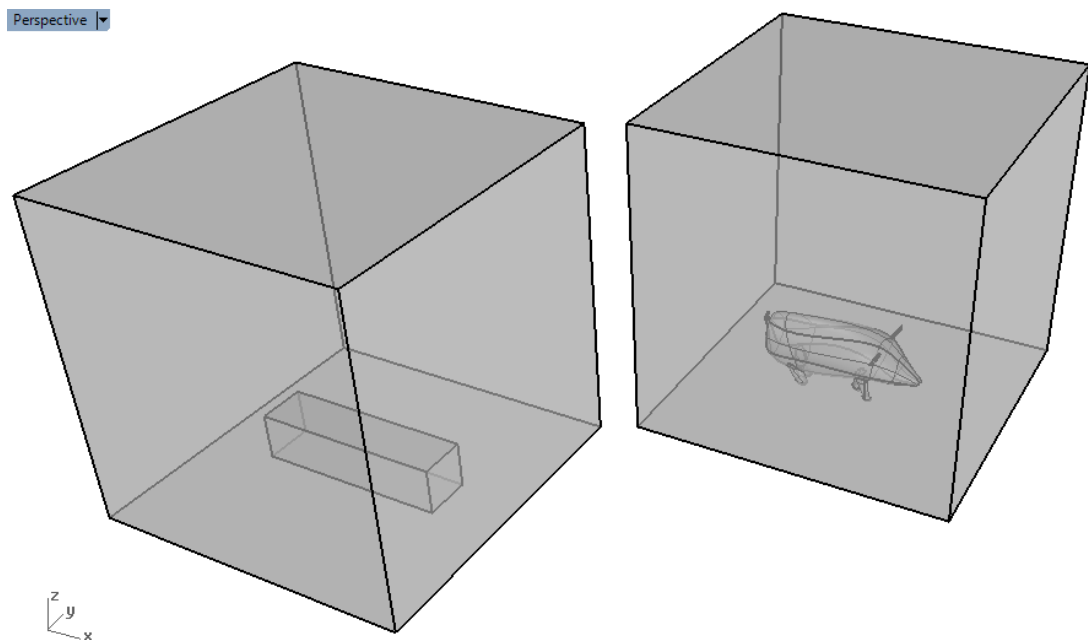


Figure 5. Establishing boundary conditions in selection of pig geometry. Font – the author.

After meshing, its quality is reviewed, for which CFD shows in a histogram on a scale from 0 to 1 (from worst to best), the quality of the elements that make up the mesh (Quality Metric Histogram, n.d.) (Figure 6). For the mesh for the installation with pigs it is necessary to reduce the number of elements and nodes by verifying the quality of the mesh, this is done to optimize simulation processes and is known as the Mesh Test. Finally, a subdivided mesh is

obtained ready to start the simulation process, and thus the modeling process ends.

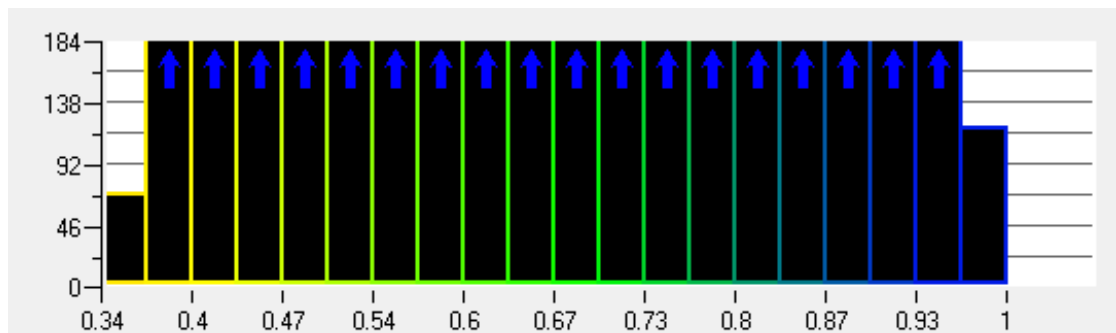


Figure 6. Quality of elements in meshing process using a histogram in mesh testing. X axis: quality of elements (0 to 1). Y axis: number of elements. Font – the author

### 3.5. Simulation of interactions of facility between the animal and the environment and data validation

The simulation process is a stationary test that starts with the previously modeled mesh, which is imported into the CFD preprocessing software. The software is worked on the Total Energy option in flow analysis, a very important step for the heat transfer input data associated with the external conditions that enter the control volume, it is also considered within CFD the compressible fluids and viscous work. A subdivision of the surfaces is carried out, according to the subdivision carried out in the modeling process.

The relevant variables of each constructive typology and animals for simulation are the previously made geometric shape (subdivision into parts), defining the climatic boundary conditions (inlet and outlet T and HR, dry bulb temperature, atmospheric pressure, relative pressure, temperature opening), ventilation characteristics (wind magnitude and direction, air inlets and outlets), construction materials (global transfer coefficient U), animal characteristics (pig heat flux). It is important to mention that the subdivision is made to determine in each of them materials, air inlet and outlets to predict the behavior of the study variables.

Additionally, in CFD preprocessing, equations were added to calculate THI (Machado et al., 2022), RH, partial vapor pressure  $e$  and the saturation vapor pressure  $e_s$ . Sensible heat production for pigs was calculated considering 60% of the total heat production. All these variables play together to validate the information obtained by the sensor kits.

By defining the equations and input variables, the software can execute a solver to analyze the environmental conditions inside the facility using a three-dimensional model and thus be able to know the behavior of the indicated variables. The climatic data (temperature (T), relative humidity (RH), temperature and humidity index (THI) and velocity ( $v$ )) calculated by CFD were compared in post-processing CFD, with the data collected by the sensor kits inside of the facilities. The results were compared by means of points distributed

in grids (Figure 3), 12 points for Facility I and Facility III, 18 for Facility II, through statistical analysis.

The simulation ends when the models of the three facilities are calibrated, statistically matching the data obtained in CFD with the data from the sensor kits, until the results are reliable. For this process, the input data in the CFD program (contour and ventilation climatic information) must be modified, adjusting them until the results coincide with those of the sensor kits, they are compared at the points, which vary according to the type of installation.

$$THI = 0.8 \cdot T_{db} + RH \cdot \left( \frac{T_{db} - 14.4}{100} \right) + 46.4 \quad (3)$$

$$RH = e \cdot 100 / e_s \quad (4)$$

$$e = e_{su} - A' \cdot P(T - T_{db}) \quad (5)$$

$$e_s = 6.1078 \cdot 10^{\left( \frac{7.5 \cdot T}{237.3 + T} \right)} \quad (6)$$

$$e_{su} = 6.1078 \cdot 10^{\left( \frac{7.5 \cdot T_{db}}{237.3 + T_{db}} \right)} \quad (7)$$

$$W_{pig} = \left( 100 + (12 * (20 - T)) \right) \cdot (0.6 / BSA) \quad (8)$$

On that, T is the temperature in °C,  $t_{db}$  is the dry air bulb temperature in °C, HR is the relative humidity of the air in %,  $W_{pig}$  is the heat production for pigs in  $W m^{-2}$ .  $A'$  is the psychrometer constant ( $0.004 \text{ } ^\circ\text{C}^{-1}$  for non-vented psychrometers), P is the atmospheric pressure in  $hPa$ .

### 3.6. Statistical Analysis

Many CFD-related studies use the ANOVA test to compare data sets to optimize CFD analyses, there are multiple examples of applications, including a study on ventilation in buildings (Yuce et al., 2022). The ANOVA test consists of a series of calculations that determine if two or more groups of data coincide statistically, Peck & Devore, (2011), mention this series of calculations starting with the total sum of squares ( $SS_t$ ), the sum of treatment squares ( $SS_{trat}$ ), error sum of squares ( $SS_{error}$ ), between-group mean square ( $MS_{trat}$ ), Within-group mean square ( $MS_{error}$ ), and  $f$ .  $p$  - value and  $f_{crit}$  are variables calculated through software.

The  $p$  - value is calculated to measure the quality of the data collected, the result is between 0-1, where the  $p$  - value results closest to 1 mean that the hypothesis is accepted. To accept the hypothesis in ANOVA, Equation 15 must be fulfilled. To statistically compare the means of each data group, the Tukey  $T_\alpha$  test (Equation 16) is used, and this is compared with the absolute value differences between the means, for each group studied.

Another comparison method widely used in this type of research is the Normalized Mean Square Error (NMSE) (Equation 17), where the control data

group (in this case, the results obtained by the sensor kits) and the group of control data are defined. of measured data (CFD). If the result is less than 0.25, it is said that the results are accepted as good indicators, as soon as the result is closer to 0, the agreement between the control and predicted data is greater.

$$SS_t = \sum_{i=1}^k \sum_{j=1}^{n_j} x_{ij}^2 - \frac{x_{..}^2}{N} \quad (9)$$

$$SS_{trat} = \sum_{j=1}^J \frac{1}{n_i} x_{i.}^2 - \frac{x_{..}^2}{N} \quad (10)$$

$$SS_{error} = SS_t - SS_{trat} \quad (11)$$

$$MS_{trat} = \frac{SS_{trat}}{k-1} \quad (12)$$

$$MS_{error} = \frac{SS_{error}}{N-k} \quad (13)$$

$$f = \frac{MS_{trat}}{MS_{error}} \quad (14)$$

$$f < f_{crit} \quad (15)$$

$$T_\alpha = q_\alpha \sqrt{\frac{MS_{error}}{n_i}} \quad (16)$$

$$NMSE = \frac{1}{n} \sum_{i=1}^n \frac{(Y_{pi} - Y_{mi})^2}{Y_{pi} Y_{mi}} \quad (17)$$

In that,  $x_{ij}$  is the element located in column "i" and row "j".  $N$  is the total number of elements.  $k$  is the total number of groups.  $n_i$  is the number of elements in group "i".  $q_\alpha$  is a Tukey parameter, it depends on  $k$  and  $N - k$ .  $Y_{pi}$  is the predicted value and  $Y_{mi}$  is the measured value.

### 3.7. Improving typological facilities

The selection of alternatives was carried out on the information validated in simulation, which allowed us to have approximations of the behavior in 3 dimensions of the variables studied (T, RH, THI and  $v$ ). Considering THI as the most relevant variable and using the average data of the points used in validation, the facilities with an average score greater than 74 were selected to propose a series of improvements (ventilation and evaporative cooling systems) and thus mitigate the alarms. of comfort. In context, the result of THI less than or equal to 74 represents thermal comfort, between 75 and 79 is thermal discomfort, 79-84 dangerous and more than 84 is emergency (Osorio et al., 2021).

Based on the above, to improve the production system of the facilities, ventilation and evaporative cooling systems were calculated, validated again using CFD to compare improvements with respect to the initial state of each facility and to be able to give improvement recommendations based on the comparative results of the mentioned variables.

The improvement proposals are first divided into modification of materials (AO1 and BO1), validation and calculation of the ventilation system only (AO2, AO3, BO2 and BO3), a modification in the dimensions and air inlet and outlet areas (AO4 and BO4), modification of dimensions and calculation of the ventilation system (AOA and BOA) and finally, a calculation of evaporative cooling (AOB and BOB).

Baêta & Souza, (2010), mention that animals in intensive production require a minimum ventilation rate to guarantee proper air circulation to maintain comfort and air quality, for 70kg pigs  $4.7m^3s^{-1}$  is recommended as air rate minimum, this for each pig. It is necessary to calculate the air renewal rate of each installation using the CFD results and the dimensions of the air inlets, with this it is possible to calculate a ventilation system that meets the minimum requirements. Knowing the velocity and the air inlet area, it is possible to calculate flow using Equation 18 (Baêta & Souza, 2010).

To improve the air flow, a ventilation system was proposed with the help of a commercial fan that provides  $7.08m^3s^{-1}$ , this equipment occupies a space of 1.2m x 1.2m in dimension SIDEKICK, (2023). From the data of a single fan and the necessary flow that must be supplied, number of fans is calculated (Equation 21), which is an integer. The fans were evenly distributed on one of the walls of each facility, promoting airflow in the predominant direction. The distance between fans (DBF) is the result of the division between the total length and F, calculated with Equation 22.

The calculation of the evaporative cooling system aims to modify the inlet conditions, improving comfort indices and reducing heat alerts (Baêta & Souza, 2010). The objective of this system is the use of inlet air humidification techniques, decreasing the temperature and increasing the relative humidity, this is calculated with the help of a psychrometric chart, it is an adiabatic cooling that reaches air saturation.

Relying on CFD, a series of input data was obtained, the current temperature and relative humidity were known, locating this psychrometric condition, the initial point is known. When the air passes through the evaporative cooling system its conditions change, the relative humidity reaches saturation and the temperature changes, from these new conditions called end point are calculated, considering an adiabatic process.

Thus, an evaporative cooling technique based on a series of nebulizers that allow the modification of the inlet conditions in the installation is proposed. the proposed nebulization system consists of a series of valves connected to a water pressure system, driven by a hydraulic pump, these pipes are installed in the upper part of the air inlets and would have a collection system in the lower part of the entrances, in order to recycle the water and that it can recirculate through the system.

$$Q_{tot} = E.A.v \quad (18)$$

$$Q_{tot\ recom} = 4.7m^3s^{-1} * AA \quad (19)$$

$$Q_{necessary} = Q_{tot} - Q_{tot\ recom} \quad (20)$$

$$F = \frac{Q_{necessary}}{Q_{vent}} = \frac{Q_{necessary}}{7.08m^3s^{-1}} \quad (21)$$

$$DBF = Total\ lenght / F \quad (22)$$

On that:  $Q_{tot}$  is Caudal in  $m^3s^{-1}$  for all facility,  $E$  is Opening effectiveness, 0.35 for agricultural constructions,  $v$  is air velocity in  $m s^{-1}$ . To evaluate the rate air condition is necessary to calculate caudal total recommended (Equation 19) to compare with total caudal if the facility meets the requirements, to calculate if the facility needs additional air flow was used Equation 20, if the result is positive, is necessary to continue the process to improve the actual conditions.

## 4. RESULTS AND DISCUSSION

### 4.1. Facility and animal modeling

Considering the variables considered in modeling mentioned in section 3.4., the models of the three selected facilities were developed, Figure 7 shows the models of the facilities, it is important to mention that the vector review was carried out for each of the models, as shows Figure 4.

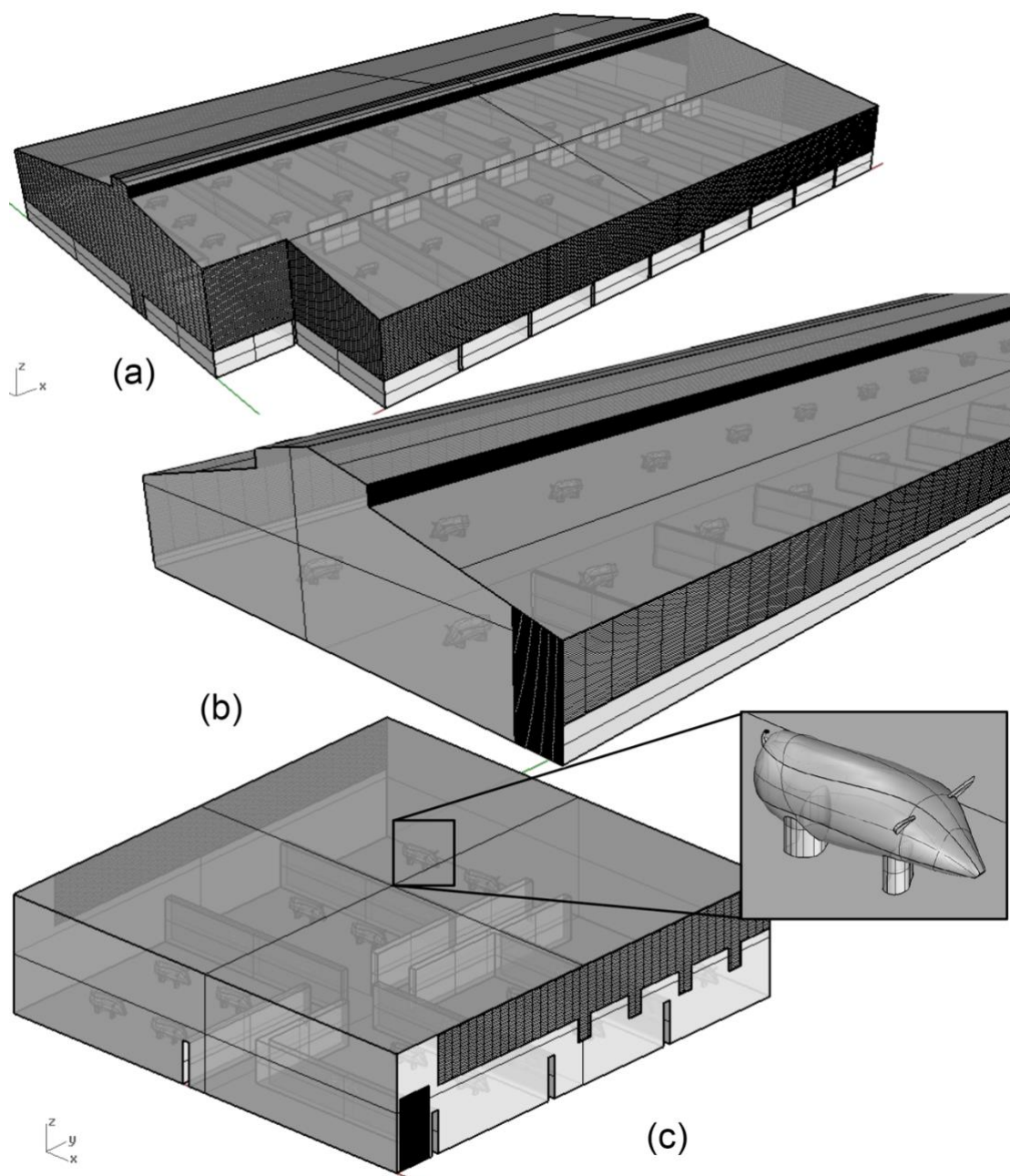


Figure 7. Modeling the three facilities, perspective view. (a) Facility I, (b) Facility II, (c) Facility III and pig model. Font – the author

Continuing with the modeling, the three geometries were reviewed to guarantee their quality, in the same way to find and correct possible errors, this is shown in Figure 8, each model was subdivided with the important elements of the installation in order to differentiate them.

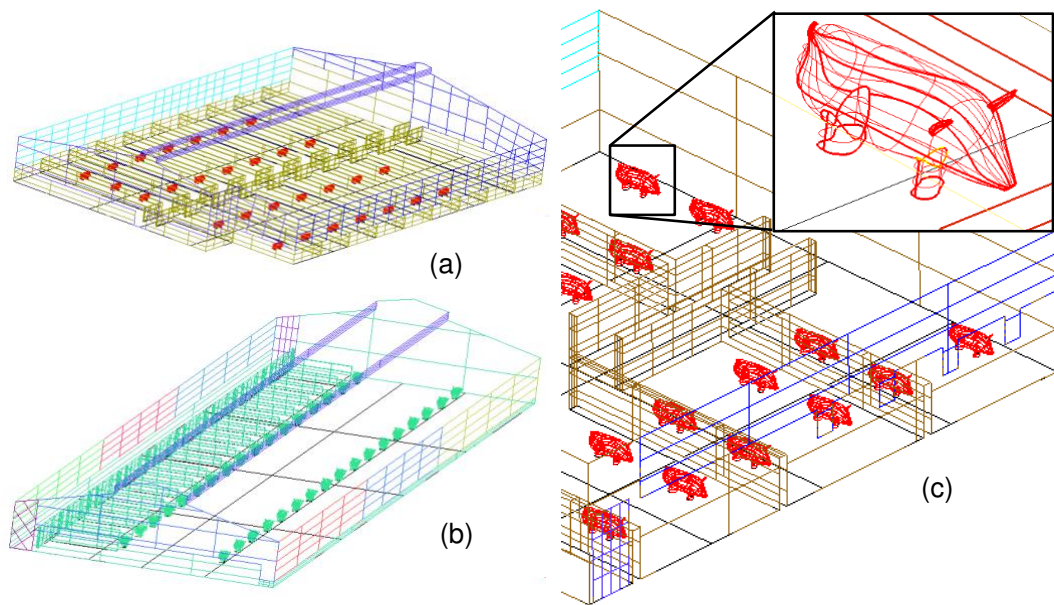


Figure 8. Geometry, subdivision, and checking geometry for the three facilities. (a) Facility I, (b) Facility II, (c) Facility III and pig model check. Font – the author

After processing the information, the different CFD meshes were created with their respective subdivisions. The results for the three facilities are shown in Figure 9. As described in section 3.4., the ceiling subdivisions were created, entrances, openings, floor, walls and pigs.

The mesh tests were carried out verifying the quality of the mesh, the resulting histograms did not show errors or problems, the results are shown in Table 6. After 6 iterations, in all cases a reduction of 58% or more in elements is obtained. and nodes.

Table 6. Validation mesh testing: Reduction of elements and nodes in 6 iterations.

| Facility | Initial Number of elements | Initial number of nodes | Final number of elements | Final number of nodes | Iteration number | percentage reduction elements | percentage reduction nodes |
|----------|----------------------------|-------------------------|--------------------------|-----------------------|------------------|-------------------------------|----------------------------|
| I        | 2058920                    | 36163                   | 797300                   | 148108                | 6                | 61%                           | 59%                        |
| II       | 2150208                    | 37828                   | 841734                   | 156134                | 6                | 61%                           | 59%                        |
| III      | 1006313                    | 17687                   | 403154                   | 74697                 | 6                | 60%                           | 58%                        |

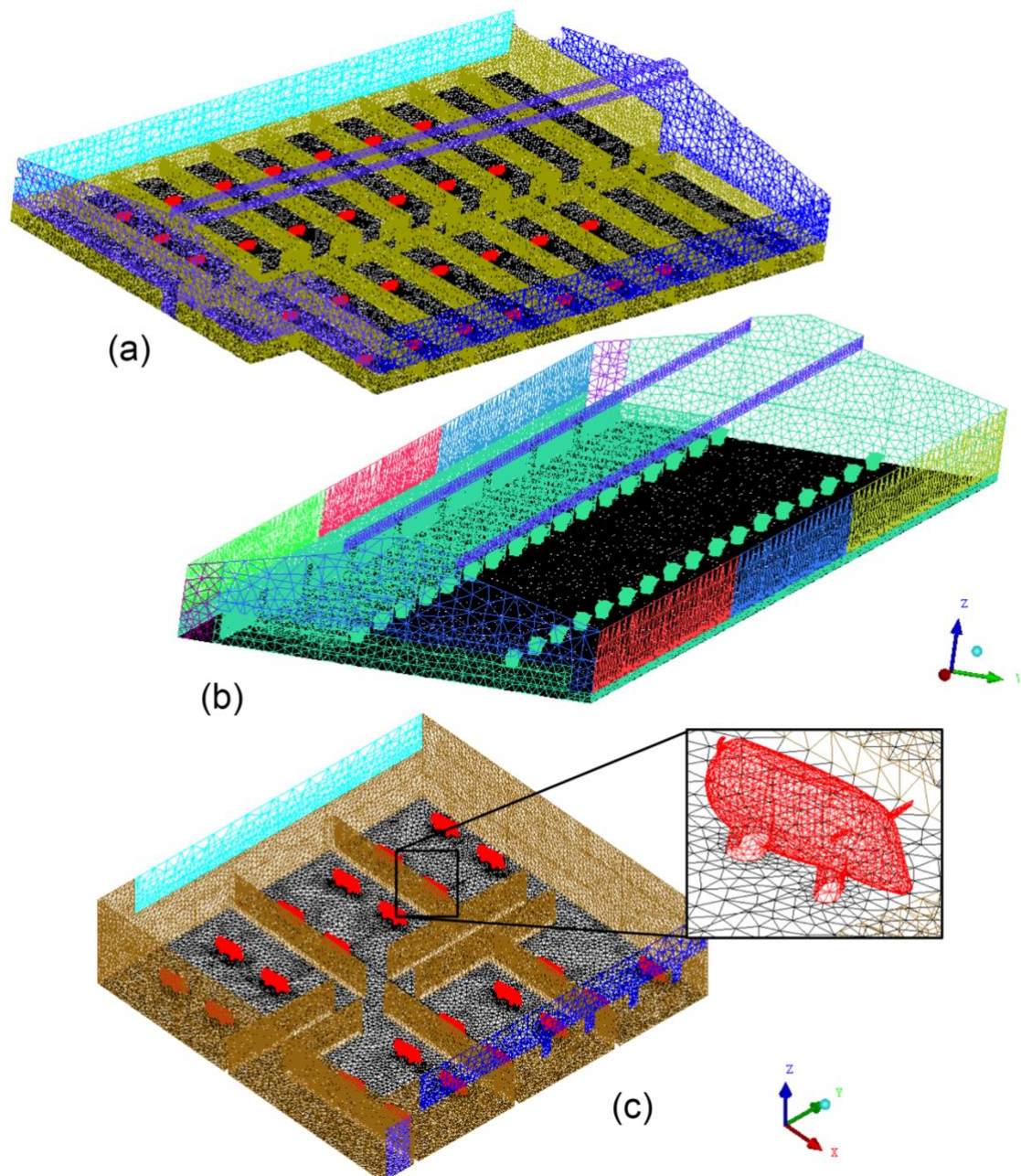


Figure 9. Facility mesh, subdivision of parts for the three facilities. (a) Facility I, (b) Facility II, (c) Facility III and pig mesh. Font – the author.

It was necessary to compare with 5 pig models to find the best option to use in simulation. The proposed models are shown in Figure 10, the geometries were named from M1 to M5, from left to right. The models have the same area calculated according to Equation 1. M1, the geometry closest to that of a pig, was drawn from the image of a pig keeping the proportions in the different parts of the body, thus favoring the closest approach to reality, so this was a geometry used as a control. M2 is the model of a box with a length that is 4 times its height, M3 is a box with the same proportion as M1, but different measurements than M2, M4 is the M1 model with a modification that increases the surface contact with the ground Using cylinders at its base, M5 was designed from M1, it has a

small enlargement in the cross-sectional area of the legs, increasing the contact area with the floor.

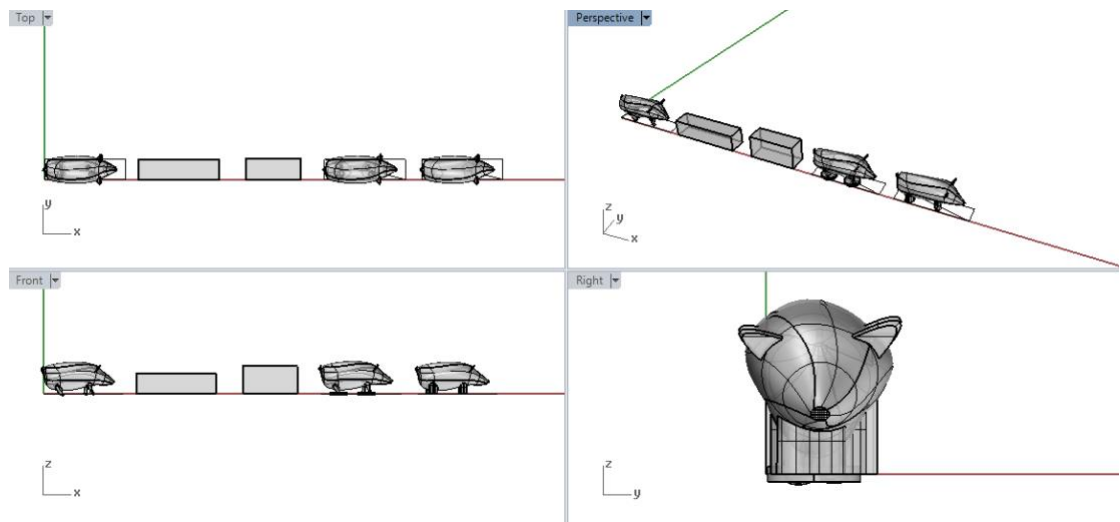


Figure 10. Swine geometries used for test and comparison. XY, perspective, XZ, and YZ view. Font – the author.

Initially, the M1 pig model was used in the facilities, a problem was found with the surfaces of the pigs and the contact with the floor, the latter was very small and required a mesh with great detail, this greatly increased the times model processing, hindering the modeling and simulation process, as shown in Figure 11. It was necessary to change the pig model to reduce the number of elements in the mesh, for this reason 5 models were proposed to select the one that It would better represent a pig and optimize process times.

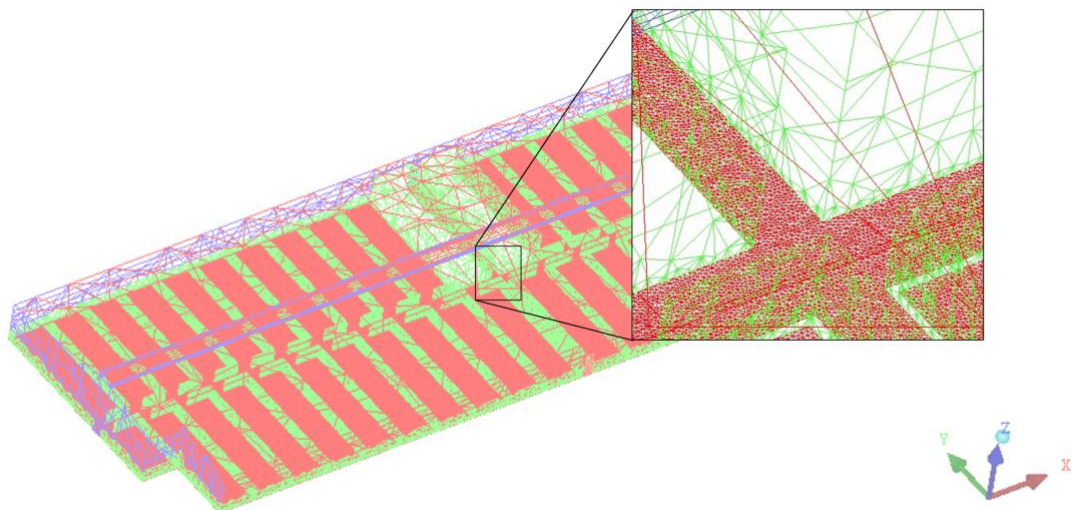


Figure 11. Mesh surpassing 20M of elements for Facility I, perspective view. Font – the author

## 4.2. Simulation of interactions and data validation

Initially, the tests were carried out with the pig models to find the best option. This simulation was carried out using one of the faces of the cube as an entrance and another as an opening, favoring a flow in the Y direction hitting the pigs laterally, the other faces of the cube were considered adiabatic walls. The simulation for the pig models was developed for all cases in a controlled condition with 295K inlet temperature,  $0.5\text{ m s}^{-1}$  inlet velocity, 296K opening temperature, 0 Pa relative opening pressure, 50% inlet relative humidity, at sea level. One of the geometries is shown in Figure 12, as an example of CFX boundary conditions.

From Equation 2 to Equation 8 were used in CFD preprocessing to know the behavior of THI, RH, T and  $v$ . The wet bulb temperature was calculated by means of the psychrometric chart, resulting in 289.15K at 0 MASL, atmospheric pressure of 1013  $hPa$ . Figure 13 shows the results of the behavior of the temperature in the simulation test for the pig.

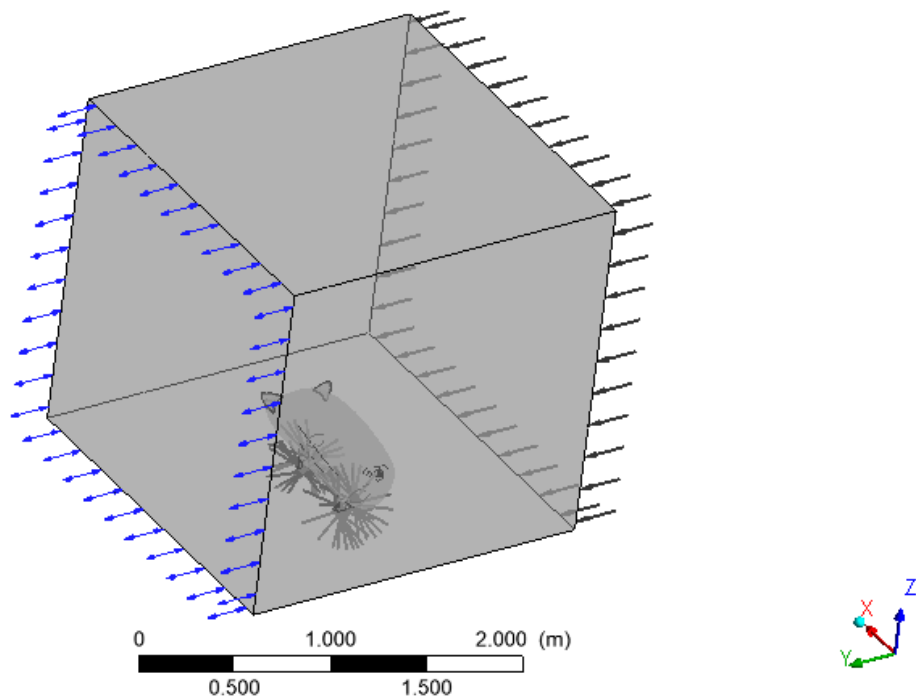


Figure 12. Establishing boundary conditions in CFX for simulation in pig geometries. Font – the author.

A total of 12 points were compared for the variables RH, T, THI,  $v$ , using the ANOVA test and using the M1 model as a control variable. Figure 14 shows the distribution and coordinates of each point. The sum, mean, and variance of each data set were calculated. Table 7 shows the average results obtained from the 5 models through CFD for the 4 variables together with their respective variance,  $T_\alpha$  was calculated using Equation 16 to compare differences between means,  $f$  was calculated using Equation 14,  $p$  – value and  $f_{crit}$  were calculated using software. From the results of the ANOVA test for RH, T, THI and  $v$  shown in Table 7, it can be seen that in all cases  $f$  is less than  $f_{crit}$ , concluding that for

the 5 geometries and the 4 variables studied, the comparison does not show significant differences.

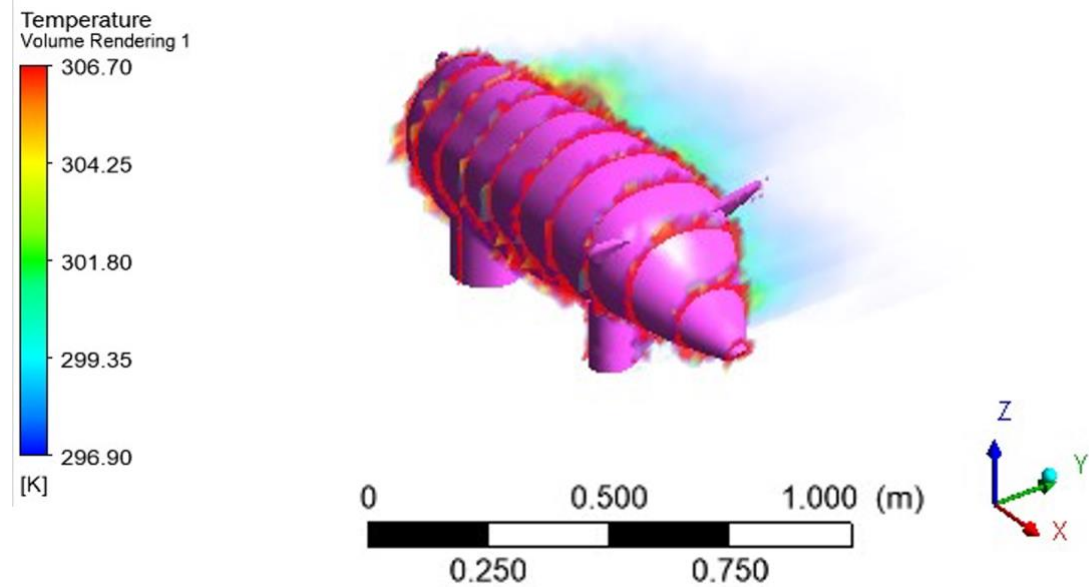


Figure 13. Test simulation for one pig for Temperature in CFD postprocessing. Font – the author.

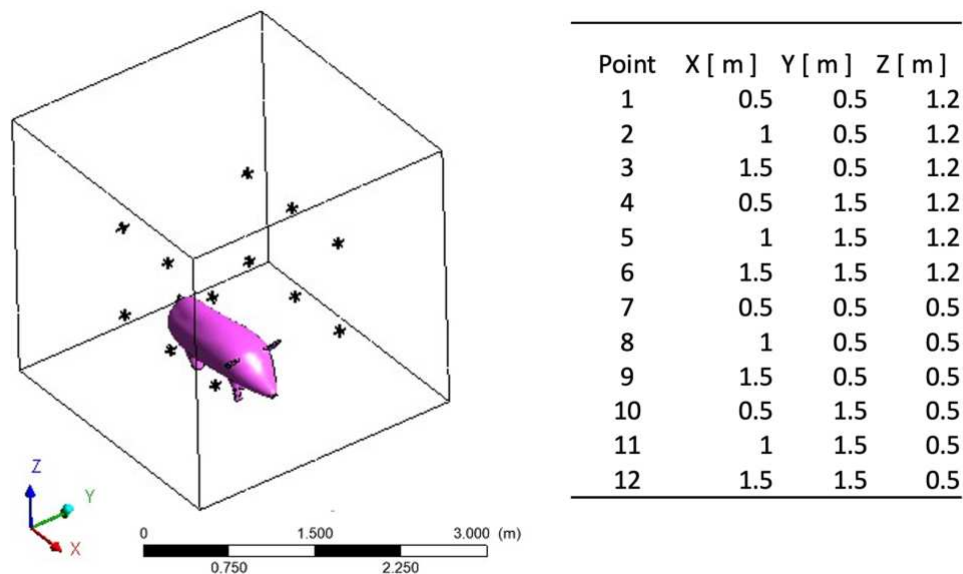


Figure 14. Point distribution and coordinates in pig test, perspective view. Font – author.

A total of 60 data were used in each variable. RH and  $v$  had the least variation between the data, although THI and T continue to show a reliable result. For Tukey's test,  $T_\alpha$  was compared with the difference between means in the different data groups (Table 8), it is shown in all cases that the average subtraction was less than  $T_\alpha$ . This means that, according to ANOVA and Tukey's test, it is possible to use any of the 5 proposed geometries.

The points located before the air passes through the pig present similar results in all cases, in contrast, the last points where the pigs pass through the air flow (points 10, 11 and 12) present differences, the behavior of the variables was higher for models M2 and M3, this may be due to the fact that they present a barrier, ignoring the air that passes between the legs of the pigs. M4 presents differences with M1 that were influenced by the cylinders drawn on the pig's feet to increase contact with the ground. M5 presents the most similar results to M1, it does not present significant variations in the behavior of the studied variables, it avoids possible turbulence that could have been generated with the other models.

Table 7. ANOVA and Tukey analysis for the 5 pig geometries, for RH, T, THI and  $v$ , average results for 5 tests, there is no significant differences for all cases  $f < f_{crit}$  represented by (\*). Font - author

| TEST                           | RH [%] | T [K]   | THI [°C] | $v [m s^{-1}]$ |
|--------------------------------|--------|---------|----------|----------------|
| <b>M1</b>                      | 50.739 | 295.095 | 67.780   | 0.517          |
| <b><math>\sigma</math> M1</b>  | 1.440  | 0.243   | 0.197    | 0.044          |
| <b>M2</b>                      | 50.492 | 295.172 | 67.814   | 0.532          |
| <b><math>\sigma</math> M2</b>  | 1.564  | 0.270   | 0.214    | 0.052          |
| <b>M3</b>                      | 50.486 | 295.137 | 67.815   | 0.518          |
| <b><math>\sigma</math> M3</b>  | 1.725  | 0.289   | 0.236    | 0.063          |
| <b>M4</b>                      | 51.196 | 295.028 | 67.718   | 0.531          |
| <b><math>\sigma</math> M4</b>  | 0.252  | 0.049   | 0.034    | 0.032          |
| <b>M5</b>                      | 51.169 | 295.022 | 67.721   | 0.529          |
| <b><math>\sigma</math> M5</b>  | 0.324  | 0.053   | 0.044    | 0.030          |
| <b><math>T_{\alpha}</math></b> | 1.498  | 0.254   | 0.205    | 0.056          |
| <b>NMSE</b>                    | 0.001  | 0.000   | 0.000    | 0.010          |
| <b>f</b>                       | 0.959  | 1.180   | 0.958    | 0.299          |
| <b>P-value</b>                 | 0.438  | 0.330   | 0.438    | 0.877          |
| <b><math>f_{crit}</math></b>   | 2.540  | 2.540   | 2.540    | 2.540          |

Table 8. Subtraction between mean samples for pig's geometries. Subtractions are followed by the same character (\*) do not differ by the Tukey test. Font – author.

| Average subtraction | RH     | T      | THI    | V      |
|---------------------|--------|--------|--------|--------|
| $\mu 1-\mu 2$       | 0.247* | 0.077* | 0.034* | 0.015* |
| $\mu 1-\mu 3$       | 0.253* | 0.042* | 0.035* | 0.002* |
| $\mu 1-\mu 4$       | 0.458* | 0.067* | 0.063* | 0.014* |
| $\mu 1-\mu 5$       | 0.430* | 0.073* | 0.059* | 0.012* |
| $\mu 2-\mu 3$       | 0.006* | 0.035* | 0.001* | 0.014* |
| $\mu 2-\mu 4$       | 0.705* | 0.144* | 0.096* | 0.002* |
| $\mu 2-\mu 5$       | 0.678* | 0.149* | 0.093* | 0.003* |
| $\mu 3-\mu 4$       | 0.711* | 0.109* | 0.097* | 0.012* |
| $\mu 3-\mu 5$       | 0.684* | 0.114* | 0.093* | 0.011* |
| $\mu 4-\mu 5$       | 0.027* | 0.005* | 0.004* | 0.001* |

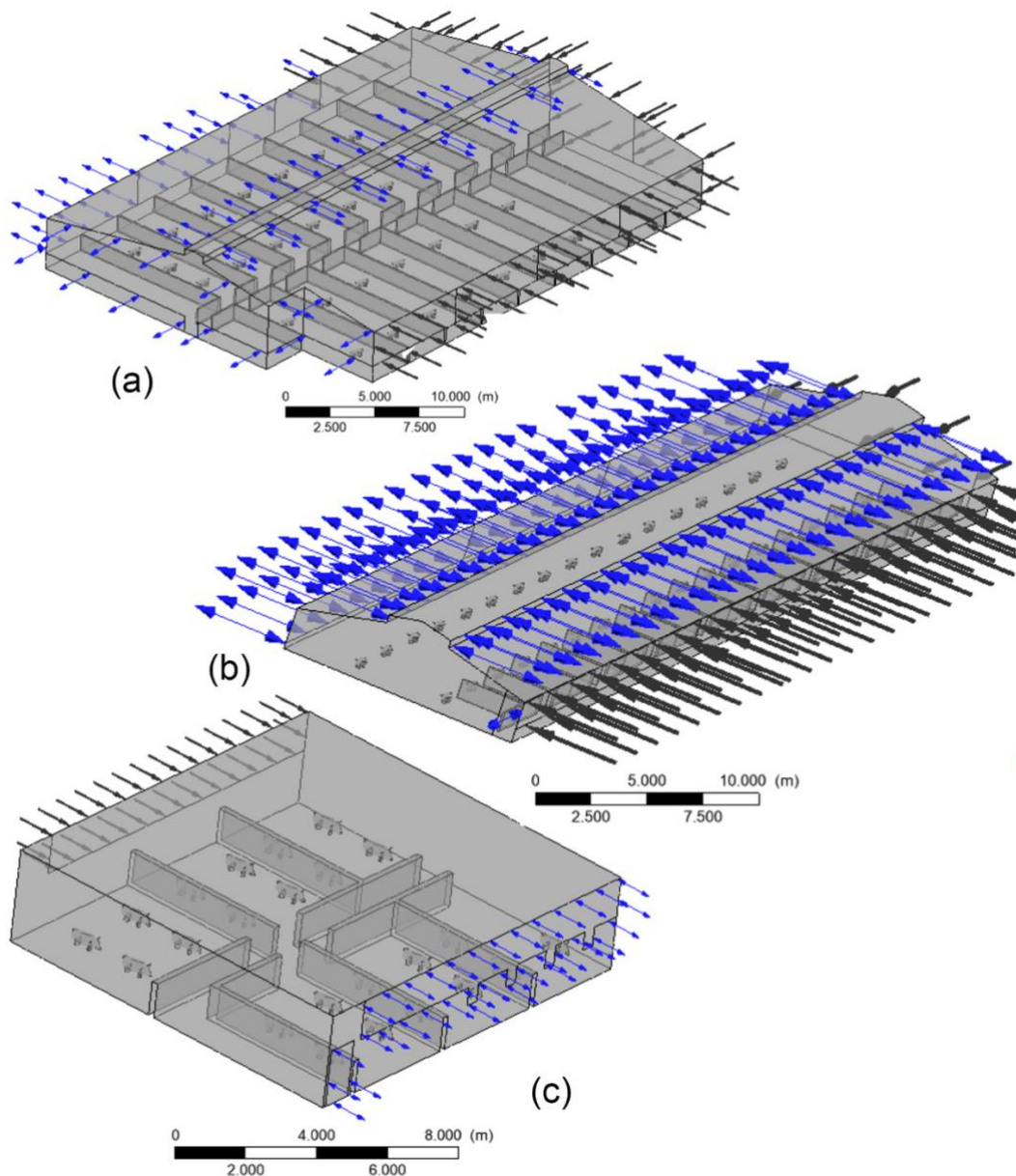


Figure 15. Use of CFX for define boundary conditions of subdivisions for inlets, openings, and walls for the three facilities. (a) Facility I, (b) Facility II, (c) Facility III. Font – the author.

M5 showed acceptable results in all variables, the contact with the ground is large enough to simplify the meshing and simulation. According to the results, all the geometries are acceptable to use, but M5 was selected for its similarity to a real pig, short entangling and simulation times, and acceptable results in the 4 variables studied. Taking M1 as control, NMSE was calculated comparing with M5 as predicted data, using Equation 17. According to the results, a value below 0.25 was obtained for NMSE, demonstrating that M5 is a statistically reliable model to use for simulation.

Continuing the simulation of the facilities and using the M5 pig model, the models were subdivided into CFD preprocessing, as described in section 3.5., the input data and equations were placed to execute the solver and thus be able

to obtain a validation of the models, the results after entering the boundary variables are shown in Figure 15, for each of the 3 facilities. Figure 16 shows the results after processing the information on CFD for THI, giving information on the behavior of this variable in 3D.

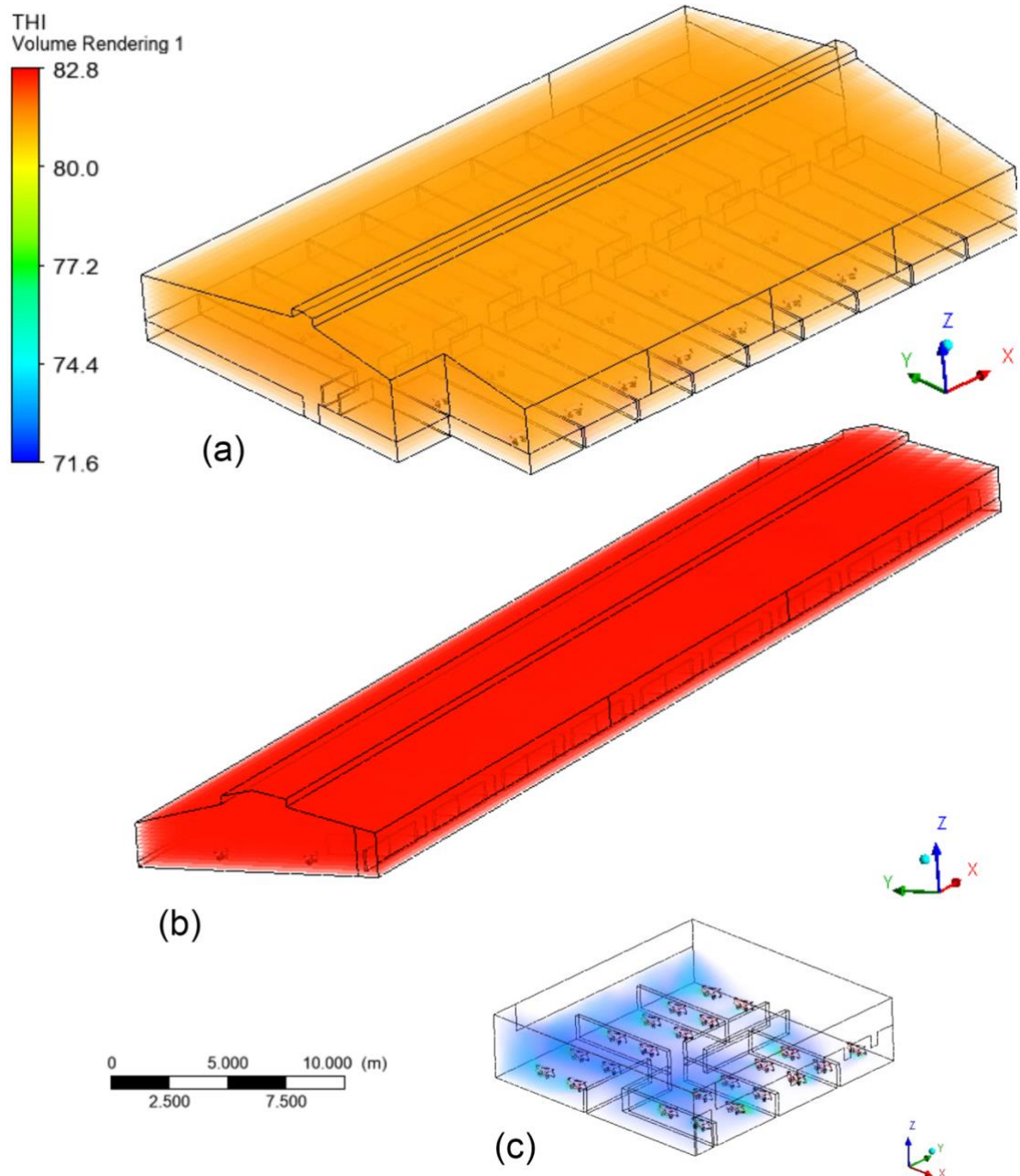


Figure 16. Graphical results of behavior of THI inside facilities, CFX postprocessing. (a) Facility I, (b) Facility I, (c) Facility III. Font – the author.

After several iterations it was possible to validate the CFD data with the information from the sensor kits, Table 9 shows the input variables used in CFD. Velocity is an input variable that needed to consider airflow in X, Y, and Z directions, perform window subdivisions, consider velocity loss caused by elements inside and outside the facility. This variable requires special care to validate CFD data with sensors.

Table 9. results after several iterations for T, RH, pressure, velocity, fan calculation, for entrance information, and modifications AOB and BOB. Font – author.

| Facility   | I      | II     | III    | AOB    | BOB    |
|--|--------|--------|--------|--------|--------|
| <b>Number of iterations</b>                      | 88     | 50     | 56     | 1.00   | 1.00   |
| <b>Outside temperature [K]</b>                   | 304.71 | 306.39 | 296.75 | 298.00 | 298.34 |
| <b>Outside RH [%]</b>                            | 58.20  | 53.29  | 69.00  | 98.00  | 98.00  |
| <b>Tdb [K]</b>                                   | 297.85 | 298.15 | 292.35 | 297.75 | 298.05 |
| <b>P [hPa]</b>                                   | 919.00 | 855.00 | 775.00 | 919.00 | 855.00 |
| <b>Inlet X speed (average) [m/s]</b>             | 0.13   | -0.19  | 1.09   |        |        |
| <b>Inlet Y speed (average) [m/s]</b>             | 0.25   | 0.69   | 0.46   |        |        |
| <b>Inlet Z speed (average) [m/s]</b>             | -0.02  | -0.02  | 0.25   |        |        |
| <b>Fan speed [m/s]</b>                           |        |        |        | 4.92   | 4.92   |
| <b><math>\Phi_{tot}</math> [W/m<sup>2</sup>]</b> | 143.38 | 143.38 | 143.38 | 143.38 | 143.38 |
| <b>Opening pressure [Pa]</b>                     | 0.00   | 0.00   | 0.00   | 0.00   | 0.00   |
| <b>Opening temperature [K]</b>                   | 305.00 | 306.44 | 297.90 | 298.26 | 298.39 |

Table 10 shows the average results obtained by CFD for the three installations, together with the average results obtained by the sensors. The results of the ANOVA test (

Table 11) show, according to the  $f_{crit}$  results, that the results obtained by CFD are statistically accepted in the studied variables (RH, T, THI and  $v$ ). Table 12 shows the results obtained by NMSE, obtaining as a result values lower than 0.25 in all cases.

Table 10. Average results for validation and CFD validation for RH, T, THI and  $v$ . Font – author.

| Facility                       | RH [%] | RH CFD [%] | T [K]  | T CFD [k] | THI [°C] | THI CFD [°C] | $v$ [m/s] | $v$ CFD [m/s] |
|--------------------------------|--------|------------|--------|-----------|----------|--------------|-----------|---------------|
| <b>I</b>                       | 55.83  | 55.62      | 304.81 | 304.84    | 81.36    | 81.36        | 0.62      | 0.52          |
| <b><math>\sigma</math> I</b>   | 1.59   | 0.43       | 0.31   | 0.09      | 0.39     | 0.05         | 0.36      | 0.21          |
| <b>II</b>                      | 50.89  | 50.63      | 306.44 | 306.50    | 82.64    | 82.67        | 0.46      | 0.45          |
| <b><math>\sigma</math> II</b>  | 2.11   | 0.30       | 0.48   | 0.07      | 0.58     | 0.04         | 0.24      | 0.17          |
| <b>III</b>                     | 63.00  | 64.55      | 297.42 | 297.16    | 72.02    | 71.81        | 0.36      | 0.34          |
| <b><math>\sigma</math> III</b> | 6.42   | 0.88       | 0.55   | 0.15      | 0.79     | 0.13         | 0.26      | 0.15          |

Table 11. ANOVA test for validation for RH, T, THI and v. Font – author.

| Facility | Variable                | RH    | T     | THI   | v     |
|----------|-------------------------|-------|-------|-------|-------|
| I        | <b>f</b>                | 0.208 | 0.095 | 0.001 | 0.637 |
|          | <b>P-value</b>          | 0.652 | 0.761 | 0.981 | 0.433 |
|          | <b>f<sub>crit</sub></b> | 4.301 | 4.301 | 4.301 | 4.301 |
| II       | <b>f</b>                | 0.200 | 0.187 | 0.022 | 0.030 |
|          | <b>P-value</b>          | 0.657 | 0.668 | 0.882 | 0.863 |
|          | <b>f<sub>crit</sub></b> | 4.130 | 4.130 | 4.130 | 4.130 |
| III      | <b>f</b>                | 0.688 | 2.511 | 0.822 | 0.046 |
|          | <b>P-value</b>          | 0.416 | 0.127 | 0.374 | 0.833 |
|          | <b>f<sub>crit</sub></b> | 4.301 | 4.301 | 4.301 | 4.301 |

Table 12. NMSE results for validation for RH, T, THI and v. Font – author.

| FACILITY | NMSE for RH | NMSE for T | NMSE for THI | NMSE for v |
|----------|-------------|------------|--------------|------------|
| I        | 0.001       | 0.000      | 0.000        | 0.246      |
| II       | 0.002       | 0.000      | 0.000        | 0.188      |
| III      | 0.010       | 0.000      | 0.000        | 0.245      |

Figure 17,

Figure 18, Figure 19, and Figure 20 show the validation results in an XY plane at Z=1.2 m, the same height where the sensors collected data, the information is for T, RH, THI and v. It is possible to see through the graphs the places where there is a high concentration of HR, T and THI, the best and worst conditions, and how these are influenced by the walls. For Facility I and Facility II it is possible to see the need to improve the comfort conditions (THI).

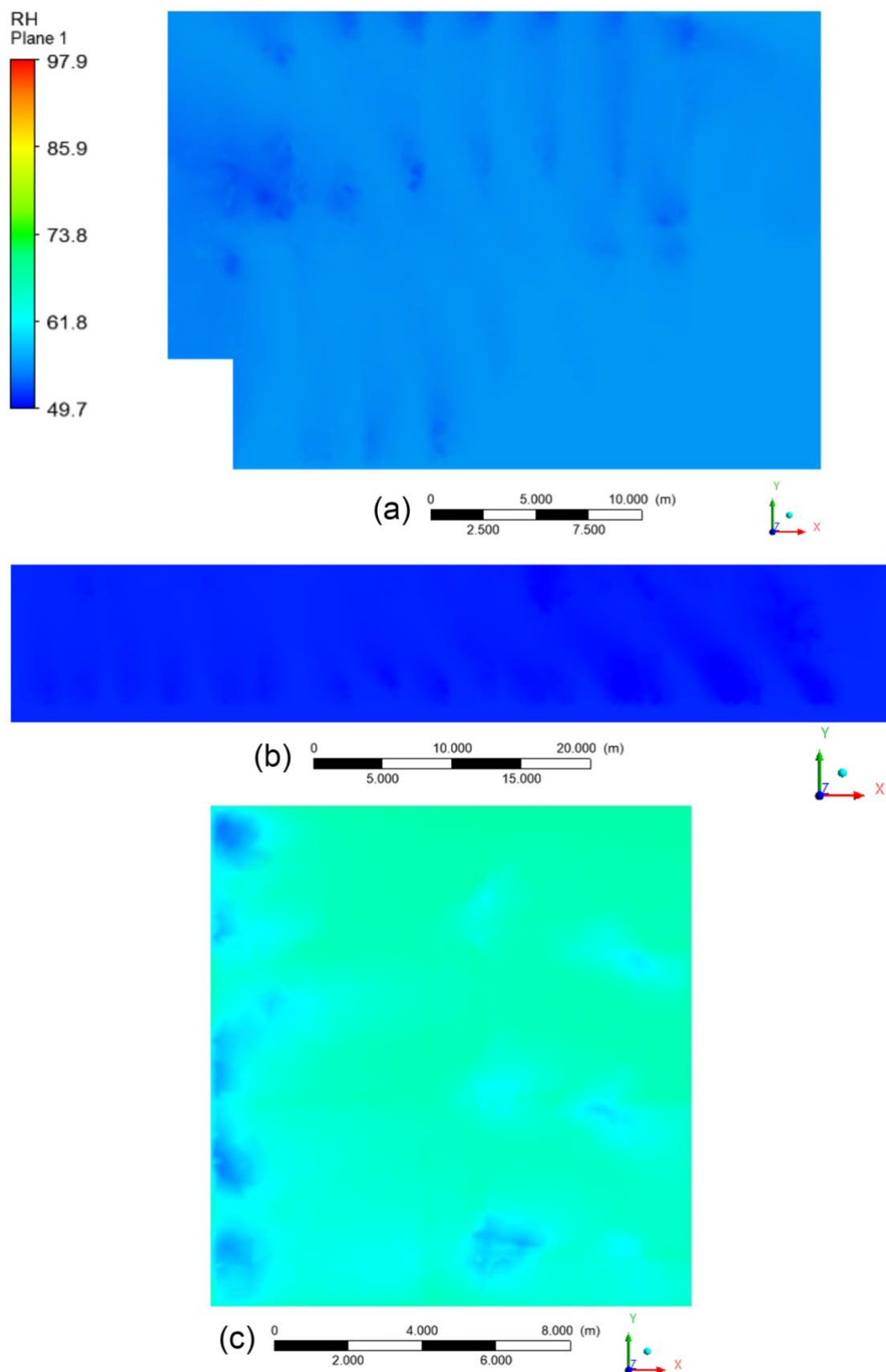


Figure 17. XY plane results of validation,  $Z=1.2\text{m}$  for RH. (a) Facility I, (b) Facility II, (c) Facility III. Font - author.

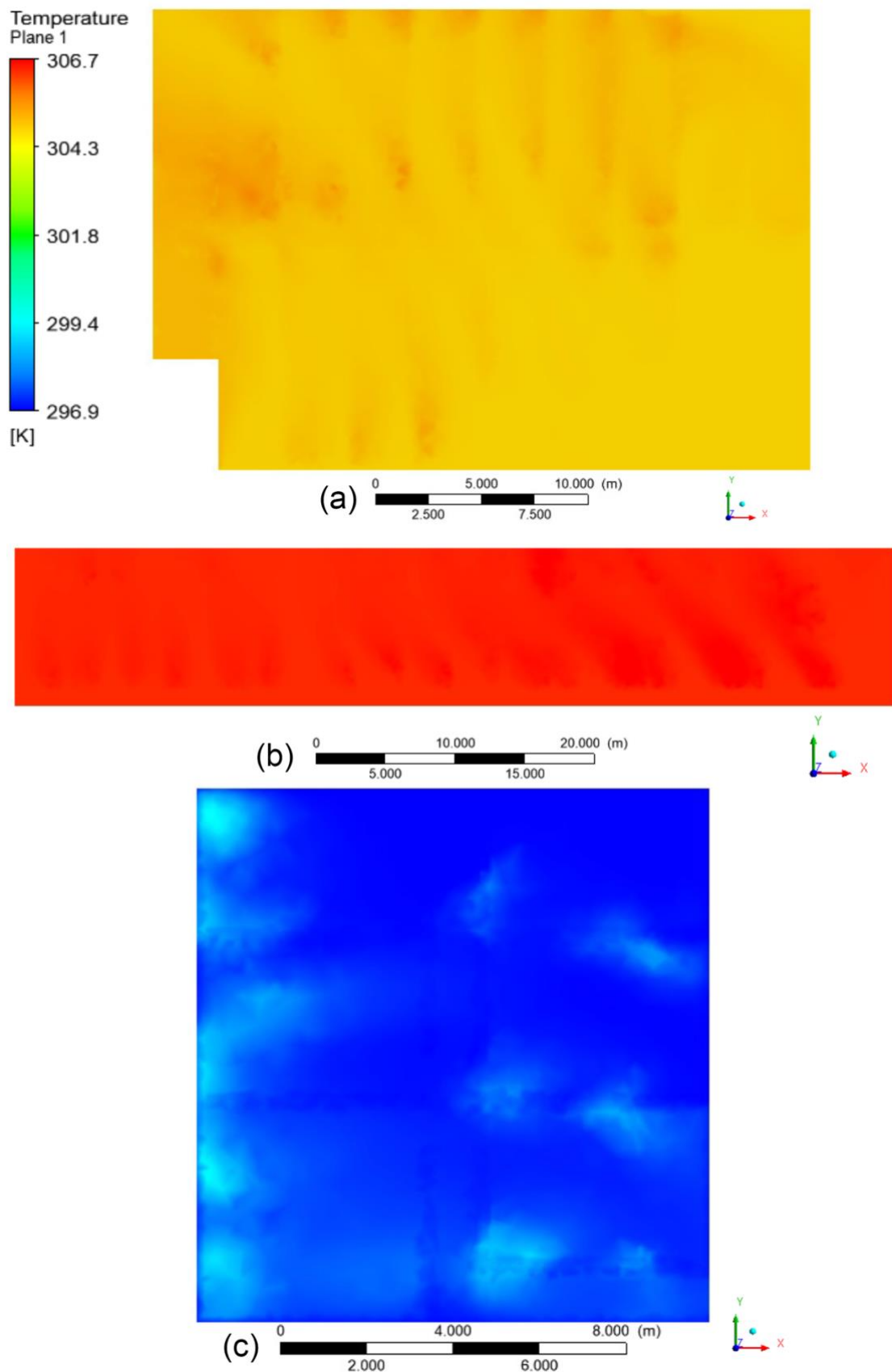


Figure 18. XY plane results of validation,  $Z=1.2\text{m}$  for Temperature. (a) Facility I, (b) Facility II, (c) Facility III. Font - author.

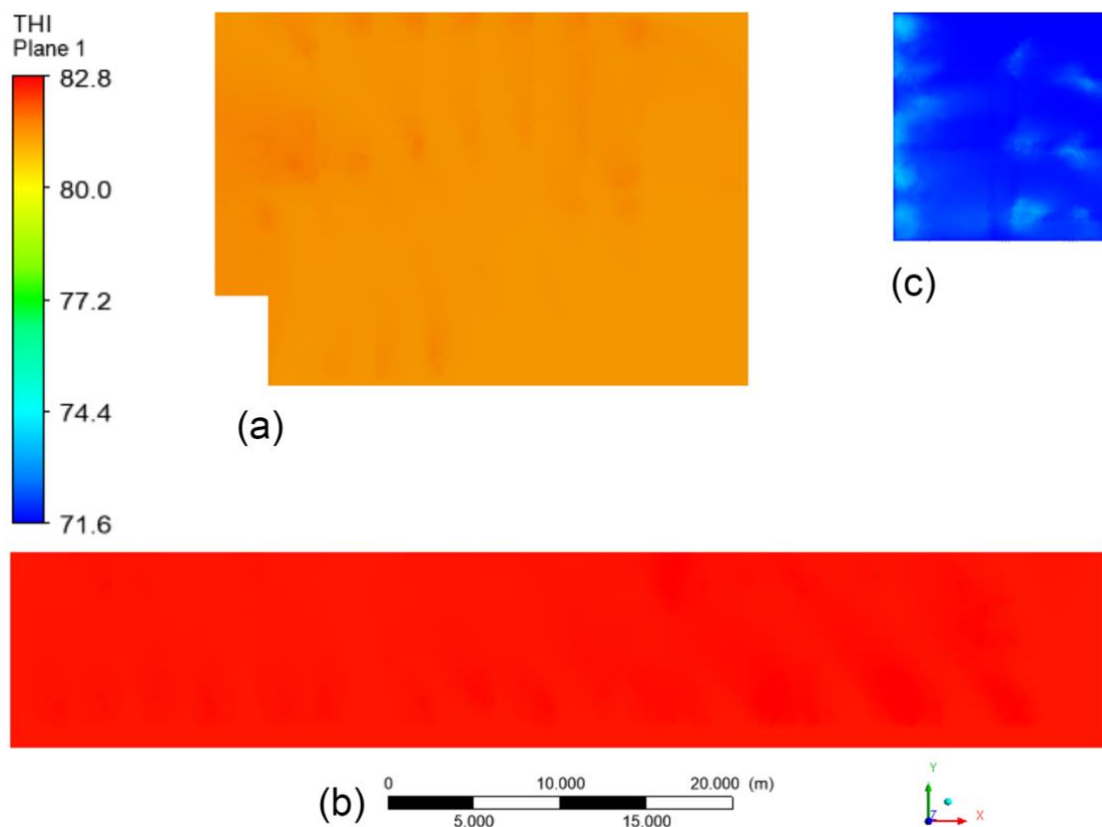


Figure 19. XY plane results of validation,  $Z=1.2\text{m}$ , THI, (a) Facility I, (b) Facility II, (c) Facility III. Font - author.

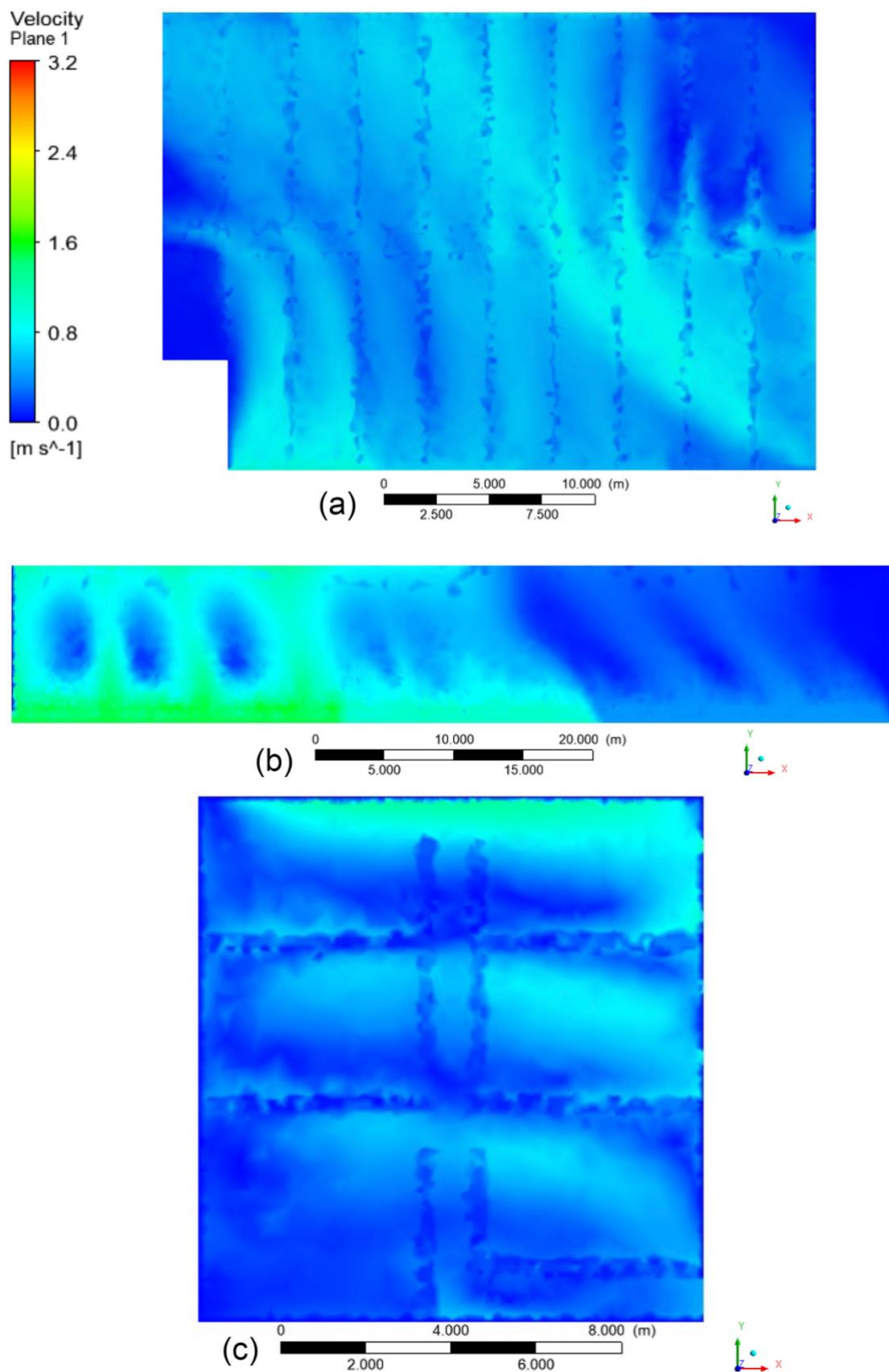


Figure 20. XY plane results of validation,  $Z=1.2\text{m}$ , velocity, (a) Facility I, (b) Facility II, (c) Facility III. Font - author.

### 4.3. Improving typological facilities

According to the validation of the information obtained by CFD for the three facilities developed in section 4.3, in Table 10 it is possible to confirm that Facility I and Facility II have the worst THI conditions, above 74, the value considered safe (Baêta & Souza, 2010). It is necessary to propose a calculation of a series of improvements for Facility I and Facility II including the modification of materials, dimensions, ventilation system and evaporative cooling.

For both facilities, the first improvement proposal (AO1 and BO1) has a modification in the roof materials, keeping the same dimensions as the validation. The second and third proposals do not have roof modifications, they have a previously calculated ventilation system, increasing only the inlet air flow, AO2 and BO2 have fans installed in the upper part of the windows, AO3 and BO3 in the lower part.

AO4 and BO4 are proposals where the internal walls that separated the spaces of the beds were eliminated, changing them for separations with metal bars, due to the size of these they were not considered in CFD, this promotes the flow and the renewal rate of the air inside installation. AOA and BOA have modification in dimensions, removal of walls and recalculated ventilation system. Proposals with the prefix "A-" correspond to Facility I and "B-" to Facility II. The dimensions were measured according to the distances as shown in Figure 1. The AOB and BOB proposals are a combination of improved roofing materials, calculated ventilation system, and evaporative cooling system.

Starting with the ventilation system (Equation 18), the entrance area was calculated, which is shown in Table 13 for Facility I, considering the same subdivision of windows used in the validation. In the same way, the air flow was calculated considering the efficiency obtained by CFD in validation, the results are shown in Table 14 for Facility I.

Continuing with the process, meshes were calculated and elements and nodes were reduced for each proposed improvement, the results are shown in Table 15 for the Facility I proposals. The ventilation system (Table 16) was calculated for the AO2 proposal. AO3 and AOA to compare the differences between the others. Using Equation 21, the number of fans is calculated, for AO2 and AO3 there is a need to install 11 fans for the first two proposals and 6 for AOA.

Table 13. Calculation of inlet area window by window for Facility I for validation and modifications. Font - author.

| <b>Inlet name</b> | <b>v Facility I [m/s]</b> | <b>Area Facility I [m<sup>2</sup>]</b> | <b>Area AO1 [m<sup>2</sup>]</b> | <b>Area AO2 [m<sup>2</sup>]</b> | <b>Area AO3 [m<sup>2</sup>]</b> | <b>Area AO4 [m<sup>2</sup>]</b> | <b>Area AOA [m<sup>2</sup>]</b> |
|-------------------|---------------------------|--|---------------------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| w21               | 0.94                      | 15.27                                  | 17.36                           | 15.27                           | 15.27                           | 22.22                           | 26.38                           |
| w22               | 0.64                      | 15.27                                  | 17.36                           | 15.27                           | 15.27                           | 22.22                           | 26.38                           |
| w23               | 0.54                      | 15.27                                  | 17.36                           | 15.27                           | 15.27                           | 22.22                           | 26.38                           |
| w24               | 0.30                      | 15.27                                  | 17.36                           | 15.27                           | 15.27                           | 22.22                           | 26.38                           |
| w31               | 0.56                      | 13.29                                  | 14.82                           | 13.29                           | 13.29                           | 18.39                           | 21.45                           |
| w32               | 0.54                      | 23.49                                  | 25.63                           | 23.49                           | 23.49                           | 28.69                           | 32.69                           |
| <b>Total</b>      |                           | 97.86                                  | 109.89                          | 97.86                           | 97.86                           | 135.96                          | 159.66                          |

Table 14. Inlet caudal calculation for Facility I for validation and modifications. Font - author

| <b>Inlet name</b>      | <b>Q Facility I [m<sup>3</sup>/s]</b> | <b>Q AO1 [m<sup>3</sup>/s]</b> | <b>Q AO2 [m<sup>3</sup>/s]</b> | <b>Q AO3 [m<sup>3</sup>/s]</b> | <b>Q AO4 [m<sup>3</sup>/s]</b> | <b>Q AOA [m<sup>3</sup>/s]</b> |
|------------------------|---------------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|--------------------------------|
| w21                    | 14.35                                 | 16.32                          | 14.35                          | 14.35                          | 20.89                          | 24.80                          |
| w22                    | 9.77                                  | 11.11                          | 9.77                           | 9.77                           | 14.22                          | 16.88                          |
| w23                    | 8.25                                  | 9.37                           | 8.25                           | 8.25                           | 12.00                          | 14.25                          |
| w24                    | 4.58                                  | 5.21                           | 4.58                           | 4.58                           | 6.67                           | 7.91                           |
| w31                    | 7.44                                  | 8.30                           | 7.44                           | 7.44                           | 10.30                          | 12.01                          |
| w32                    | 12.68                                 | 13.84                          | 12.68                          | 12.68                          | 15.49                          | 17.65                          |
| <i>Q<sub>tot</sub></i> | 57.08                                 | 64.15                          | 57.08                          | 57.08                          | 79.56                          | 93.50                          |

Table 15. Reduction of elements and nodes for meshes for optimization, Facility I. Font - author.

| <b>Optimization</b> | <b>Initial Number of elements</b> | <b>Initial number of nodes</b> | <b>Final number of elements</b> | <b>Final number of nodes</b> | <b>Iteration number</b> | <b>percent age reduction element s</b> | <b>percent age reduction on nodes</b> |
|---------------------|-----------------------------------|--------------------------------|---------------------------------|------------------------------|-------------------------|--|---------------------------------------|
| <b>AO1</b>          | 208193                            | 366126                         | 818100                          | 152447                       | 6                       | 61%                                    | 58%                                   |
| <b>AO2</b>          | 201558                            | 354305                         | 786564                          | 146079                       | 6                       | 61%                                    | 59%                                   |
| <b>AO3</b>          | 180822                            | 318989                         | 743687                          | 138243                       | 6                       | 59%                                    | 57%                                   |
| <b>AO4</b>          | 176038                            | 310492                         | 692955                          | 129037                       | 6                       | 61%                                    | 58%                                   |
| <b>AOA</b>          | 171895                            | 303726                         | 691972                          | 128965                       | 6                       | 60%                                    | 58%                                   |

Table 16. Ventilation calculation for Facility I, validation and modifications. Font - author.

|  | Facility I | AO1    | AO2    | AO3    | AO4    | AOA    |
|--|------------|--------|--------|--------|--------|--------|
| <b>Total area of Inlet [m<sup>2</sup>]</b> | 97.86      | 109.89 | 97.86  | 97.86  | 135.96 | 159.66 |
| <b>Qtot [m<sup>3</sup>/s]</b>              | 57.08      | 64.15  | 57.08  | 57.08  | 79.56  | 93.50  |
| <b>AA []</b>                               | 29         | 29     | 29     | 29     | 29     | 29     |
| <b>Q/pig [m<sup>3</sup>/s]</b>             | 1.97       | 2.21   | 1.97   | 1.97   | 2.74   | 3.22   |
| <b>Q/pig recommended [m<sup>3</sup>/s]</b> | 4.70       | 4.70   | 4.70   | 4.70   | 4.70   | 4.70   |
| <b>Qtot recommended [m<sup>3</sup>/s]</b>  | 136.30     | 136.30 | 136.30 | 136.30 | 136.30 | 136.30 |
| <b>Q necessary [m<sup>3</sup>/s]</b>       | 79.22      | 72.15  | 79.22  | 79.22  | 56.74  | 42.80  |
| <b>Q per fan [m<sup>3</sup>/s]</b>         | 7.08       | 7.08   | 7.08   | 7.08   | 7.08   | 7.08   |
| <b>F []</b>                                |            |        | 11     | 11     |        | 6      |
| <b>Total length [m]</b>                    |            |        | 27.77  | 27.77  |        | 27.77  |
| <b>DBF [m]</b>                             |            |        | 2.48   | 2.48   |        | 4.59   |
| <b>Area fan [m<sup>2</sup>]</b>            |            |        | 1.44   | 1.44   |        | 1.44   |
| <b>Velocity fan [m/s]</b>                  |            |        | 4.92   | 4.92   |        | 4.92   |

The entrance area, shown in Table 17, was calculated for the proposed improvements in Facility II. Thus, the air flow was calculated considering the efficiency, the data was obtained by CFD in validation and is shown in Table 18 for Facility II. Meshes were calculated and elements and nodes were reduced for each improvement proposal, the results are shown in Table 19 for the Facility II proposals. The ventilation system (Table 20) was calculated for the BO2, BO3 and BOA proposals. Using Equation 21, the number of necessary fans was calculated, there is a need to install 12 BO2 and BO3 fans, BOA does not require fans.

Table 17. Calculation of inlet area for Facility II for validation and modifications, window by window. Font - author.

| Inlet name | v Facility II [m/s] | A Facility II [m <sup>2</sup> ] | A BO1 [m <sup>2</sup> ] | A BO2 [m <sup>2</sup> ] | A BO3 [m <sup>2</sup> ] | A BO4 [m <sup>2</sup> ] | A BOA [m <sup>2</sup> ] |
|------------|---------------------|---------------------------------|-------------------------|-------------------------|-------------------------|-------------------------|-------------------------|
| w1         | 0.02                | 21.98                           | 28.58                   | 21.98                   | 21.98                   | 30.94                   | 40.93                   |
| w21        | 0.35                | 28.44                           | 40.07                   | 28.44                   | 28.44                   | 42.22                   | 60.32                   |
| w22        | 0.90                | 24.04                           | 33.88                   | 24.04                   | 24.04                   | 35.7                    | 51                      |
| w23        | 1.50                | 31.47                           | 44.35                   | 31.47                   | 31.47                   | 46.74                   | 66.77                   |
| total      |                     | 105.93                          | 146.88                  | 105.93                  | 105.93                  | 155.6                   | 219.02                  |

Table 18. Inlet caudal calculation for ventilation, Facility II for validation and modifications, window by window. Font – author.

| Inlet name             | Q Facility II [m <sup>3</sup> /s] | Q BO1 [m <sup>3</sup> /s] | Q BO2 [m <sup>3</sup> /s] | Q BO3 [m <sup>3</sup> /s] | Q BO4 [m <sup>3</sup> /s] | Q BOA [m <sup>3</sup> /s] |
|------------------------|-----------------------------------|---------------------------|---------------------------|---------------------------|---------------------------|---------------------------|
| w1                     | 0.44                              | 0.57                      | 0.44                      | 0.44                      | 0.62                      | 0.82                      |
| w21                    | 9.95                              | 14.02                     | 9.95                      | 9.95                      | 14.78                     | 21.11                     |
| w22                    | 21.64                             | 30.49                     | 21.64                     | 21.64                     | 32.13                     | 45.90                     |
| w23                    | 47.21                             | 66.53                     | 47.21                     | 47.21                     | 70.11                     | 100.16                    |
| <i>Q<sub>tot</sub></i> | 79.23                             | 111.61                    | 79.23                     | 79.23                     | 117.64                    | 167.99                    |

Table 19. Reduction of elements and nodes for meshes for optimization, Facility II for modifications. Font - author.

| Optimization | Initial Number of elements | Initial number of nodes | Final number of elements | Final number of nodes | Iteration number | percent age reduction on elements | percent age reduction on nodes |
|--------------|----------------------------|-------------------------|--------------------------|-----------------------|------------------|-----------------------------------|--------------------------------|
| BO1          | 2246494                    | 395132                  | 888126                   | 164736                | 6                | 60%                               | 58%                            |
| BO2          | 2156631                    | 379360                  | 841913                   | 156192                | 6                | 61%                               | 59%                            |
| BO3          | 2721182                    | 479361                  | 1185293                  | 217002                | 6                | 56%                               | 55%                            |
| BO4          | 2108725                    | 371233                  | 820483                   | 152853                | 6                | 61%                               | 59%                            |
| BOA          | 2020172                    | 356785                  | 809660                   | 150861                | 6                | 60%                               | 58%                            |

Table 20. Total areas, caudal, and fan calculation for Facility II for validation and modifications. Font - author.

|                                       | Facility II | BO1    | BO2    | BO3    | BO4    | BOA    |
|---------------------------------------|-------------|--------|--------|--------|--------|--------|
| Total area of Inlet [m <sup>2</sup> ] | 105.93      | 146.88 | 105.93 | 105.93 | 155.6  | 219.02 |
| Qtot [m <sup>3</sup> /s]              | 79.23       | 111.61 | 79.23  | 79.23  | 117.64 | 167.99 |
| AA []                                 | 34          | 34     | 34     | 34     | 34     | 34     |
| Q/pig [m <sup>3</sup> /s]             | 2.33        | 3.28   | 2.33   | 2.33   | 3.46   | 4.94   |
| Q/pig recommended [m <sup>3</sup> /s] | 4.70        | 4.70   | 4.70   | 4.70   | 4.70   | 4.70   |
| Qtot recommended [m <sup>3</sup> /s]  | 159.80      | 159.80 | 159.80 | 159.80 | 159.80 | 159.80 |
| Q necessary [m <sup>3</sup> /s]       | 80.57       | 48.19  | 80.57  | 80.57  | 42.16  | 0.00   |
| Q per fan [m <sup>3</sup> /s]         |             |        | 7.08   | 7.08   |        |        |
| F []                                  |             |        | 12     | 12     |        |        |
| Total length [m]                      |             |        | 63.6   | 63.6   |        |        |
| DBF [m]                               |             |        | 5.30   | 5.30   |        |        |
| Area fan [m <sup>2</sup> ]            |             |        | 1.44   | 1.44   |        |        |
| Velocity fan [m/s]                    |             |        | 4.92   | 4.92   |        |        |

The summary, the modifications of dimensions, materials, ventilation systems and evaporative cooling for Facility I and Facility II are shown in Table 21. Figure 21 shows in view YZ and XZ the modifications made for the AOB proposal where the walls separating the beds were eliminated, increasing the total and ceiling height, the calculated areas are shown also in Table 21. For a better interpretation, an isometric view is shown in Figure 22 for Facility I, mentioning the main modifications made in AOB.

Table 21. Modifications in dimensions, inlet and opening areas, materials, ventilation and evaporative cooling systems made for each modification. Font - author.

| <b>Optimization</b> | <b>Total height [m]</b> | <b>Inlet windows height [m]</b> | <b>Inlet area [m<sup>2</sup>]</b> | <b>ceiling opening height [m]</b> | <b>Opening area [m<sup>2</sup>]</b> | <b>Kind of ceiling</b>      | <b>Ventilation system</b> | <b>Evaporative cooling system</b> |
|---------------------|-------------------------|---------------------------------|-----------------------------------|-----------------------------------|-------------------------------------|-----------------------------|---------------------------|-----------------------------------|
| <b>AO1</b>          | 5.33                    | 2.20                            | 97.87                             | 0.40                              | 185.48                              | Clay tile<br>8cm            | no                        | no                                |
| <b>AO2</b>          | 5.33                    | 2.20                            | 97.87                             | 0.40                              | 185.48                              | Zinc tile                   | yes                       | no                                |
| <b>AO3</b>          | 5.33                    | 2.20                            | 97.87                             | 0.40                              | 185.48                              | Zinc tile                   | yes                       | no                                |
| <b>AO4</b>          | 5.33                    | 3.20                            | 135.94                            | 0.40                              | 239.92                              | Zinc tile                   | no                        | no                                |
| <b>AOA</b>          | 6.22                    | 3.80                            | 159.64                            | 0.70                              | 298.56                              | Clay tile<br>8cm            | yes                       | no                                |
| <b>AOB</b>          | 6.22                    | 3.80                            | 159.64                            | 0.70                              | 298.56                              | Clay tile<br>8cm            | yes                       | yes                               |
| <b>BO1</b>          | 3.62                    | 1.32                            | 105.94                            | 0.35                              | 155.20                              | Clay tile<br>8cm            | no                        | no                                |
| <b>BO2</b>          | 3.62                    | 1.32                            | 105.94                            | 0.35                              | 155.20                              | Asbestos cement<br>tile 5mm | yes                       | no                                |
| <b>BO3</b>          | 3.62                    | 1.32                            | 105.94                            | 0.35                              | 155.20                              | Asbestos cement<br>tile 5mm | yes                       | no                                |
| <b>BO4</b>          | 3.62                    | 1.96                            | 155.60                            | 0.35                              | 171.74                              | Asbestos cement<br>tile 5mm | no                        | no                                |
| <b>BOA</b>          | 4.61                    | 2.80                            | 219.02                            | 0.50                              | 245.06                              | Clay tile<br>8cm            | no                        | no                                |
| <b>BOB</b>          | 4.61                    | 2.80                            | 219.02                            | 0.50                              | 245.06                              | Clay tile<br>8cm            | no                        | yes                               |

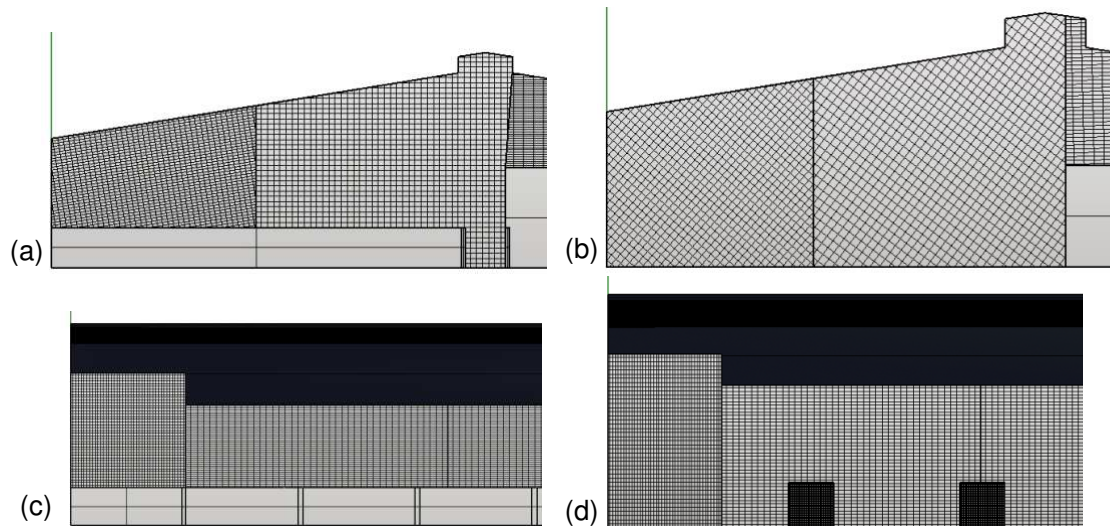


Figure 21. Modifications proposed for Facility I to improve the hygrothermal environment. (a) Facility I, without modifications. YZ view, (b) Facility I, modifications in walls, ceiling and total height. YZ view, (c) Facility I, without modifications. XZ view, (d) Facility I, modifications in walls, ceiling and total height, ventilation and evaporative cooling system. XZ view. Font - author.

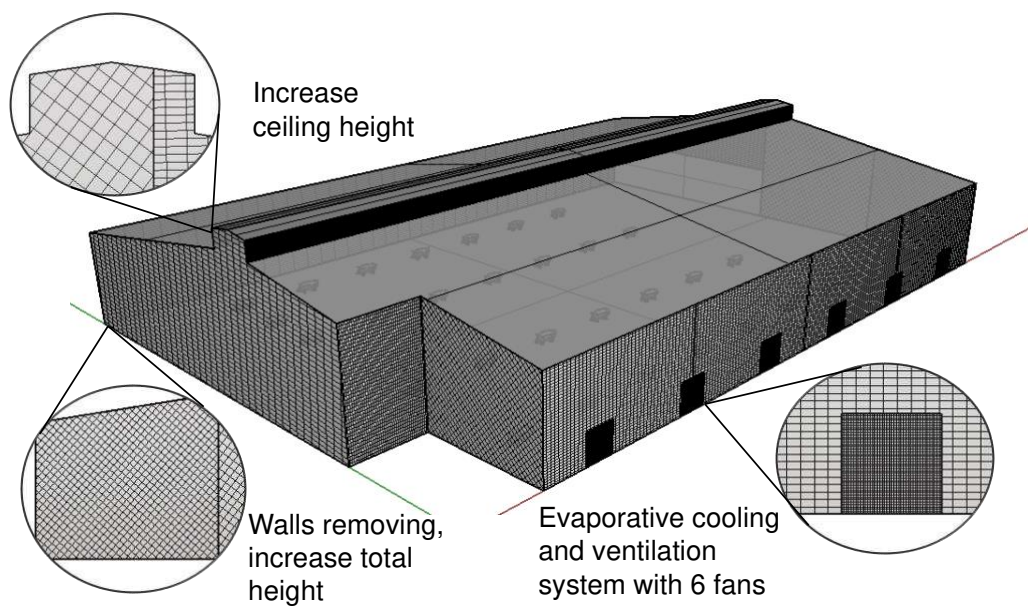


Figure 22. Geometry with the AOB modifications to improve the hygrothermal environment. Font - author.

Figure 23 shows in the YZ and XZ view the modifications made to the BOB proposal where the walls separating the beds were eliminated, increasing the total and ceiling height, the areas are shown in Table 21. An isometric view is shown in Figure 24 for Facility II, mentioning the main modifications made in BOB.

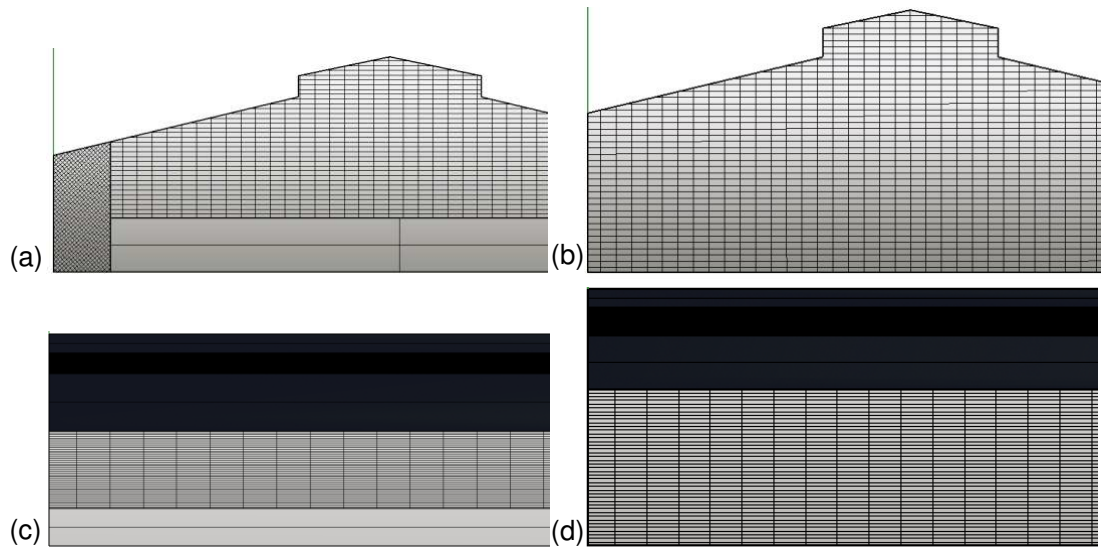


Figure 23. Modifications proposed for Facility II to improve the hygrothermal environment. (a) Facility II, without modifications. YZ view, (b) Facility II, modifications in walls, ceiling and total height. YZ view, (c) Facility II, without modifications. XZ view, (d) Facility II, modifications in walls, ceiling and total height, evaporative cooling system. XZ view. Font - author.

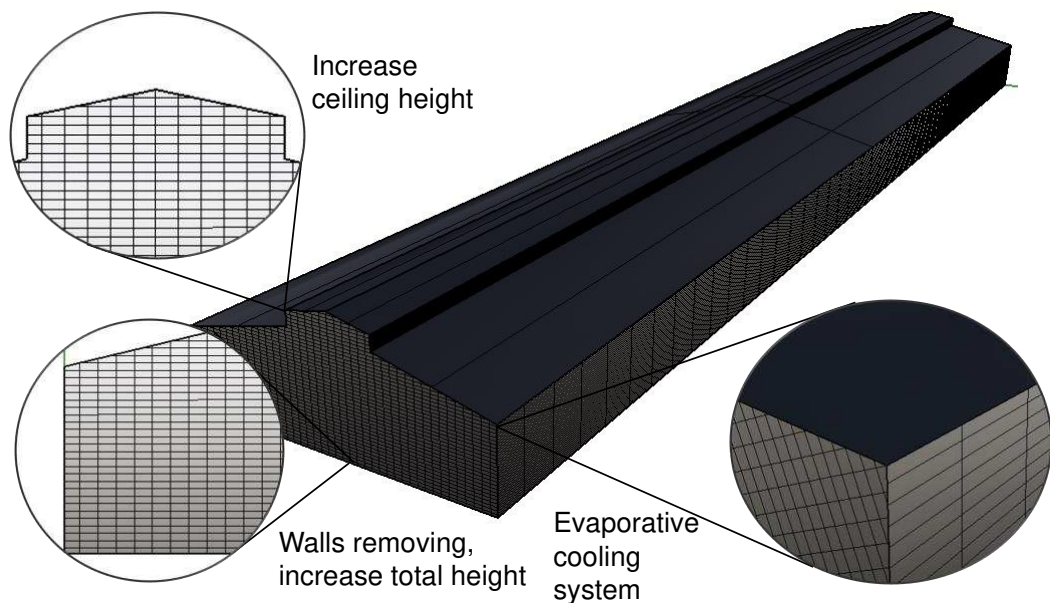


Figure 24. Geometry with the BOB modifications to improve the hygrothermal environment. Font - author.

Figure 25 and Figure 26 show the differences between the input and opening window proposals starting with AO1 and BO1 and ending with the AOB and BOB proposal. The calculated evaporative cooling is a nebulization system that uses a distributed system of pressurized water throwing windows, this combined with the humidity of the roof and walls, modify the conditions of entry into the facilities. With the help of the psychrometric chart and considering a highly efficient humidity of the air, an evaporative cooling process was considered, being an adiabatic process. The input conditions calculated by the psychrometric chart used in CFD for the simulation are shown in

Table 9 for AOA and BOA.

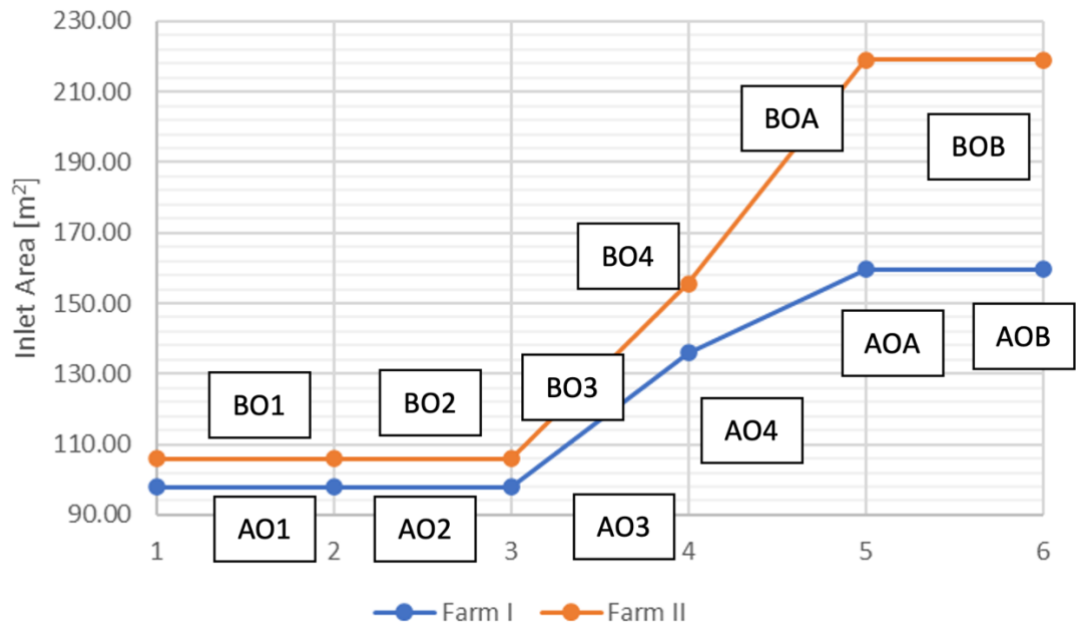


Figure 25. Changes in inlet Area [ $m^2$ ] for Facility I and Facility II for the 6 improvement proposals. Font - author.

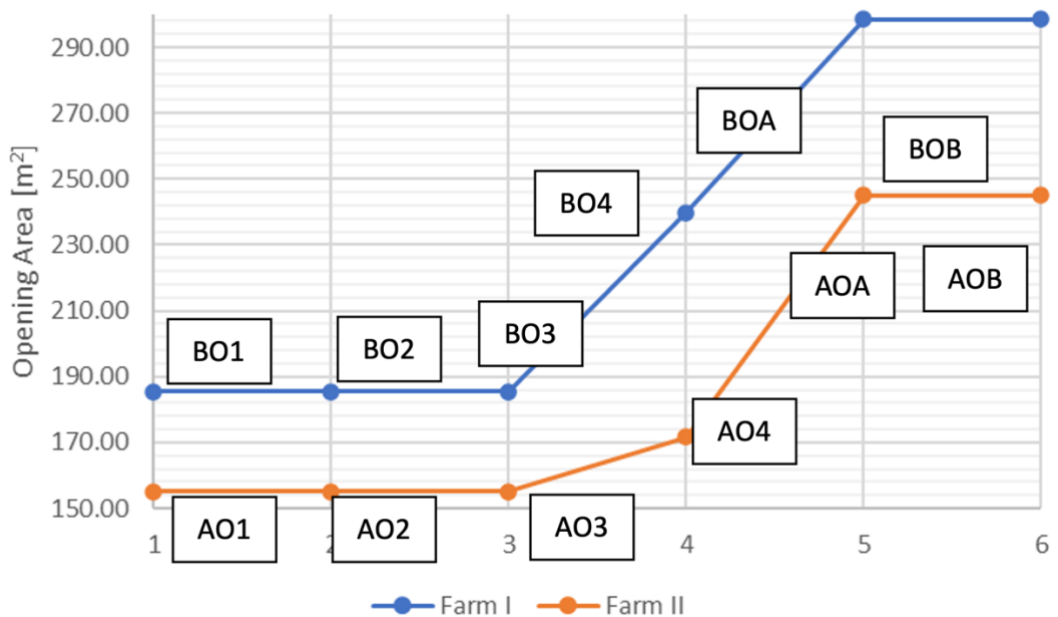


Figure 26. Changes in opening Area [ $m^2$ ] for Facility I and Facility II for the 6 improvement proposals. Font - author.

Using the same validation points for Facility I and Facility II, the average results for RH, T, THI and  $v$  were calculated. For Facility I (Table 22), the modifications in the roof represented a decrease of  $0.01\text{ }^\circ\text{C}$  for THI and the same conditions in the ventilation. Comparing the installations of the fans in the lower and upper part of the windows, the first one shows better conditions for THI and  $v$ , decreasing THI by  $0.04\text{ }^\circ\text{C}$  and improving by  $1.2\text{ m s}^{-1}$  compared to

the validation. AO4 shows a decrease in THI of 0.05°C and an increase of 0.29  $m s^{-1}$  in airflow. AOA took into consideration the fans at the bottom of the windows and THI decreased by 0.06°C, increased by 1.27  $m s^{-1}$  the airflow.

For AOB, the evaporative cooling system shows an overall decrease in THI of 4.84°C and an increase in 1.27  $m s^{-1}$  for air velocity. AOB is the best option calculated to improve comfort, according to the results shown in Table 22, the graphical results are shown in Figure 27 for RH, Figure 28 for T, Figure 29 for THI, and Figure 30 for  $v$  to better understand the behavior of AOB and BOB optimization. Figure 33 shows the area involved in the evaporative cooling system. Installing a ventilation system close to the height of the pig will improve the air rate meeting the recommendations, and the evaporative cooling system helps decrease the THI index improving comfort. It is possible to combine an evaporative system with the increase in height, these are the most representative changes according to the results.

Table 22. Average results for RH, T, THI and  $v$  for optimization, Facility I. Font - author

|                                       | <b>RH [%]</b> | <b>T [K]</b> | <b>THI [°C]</b> | <b>v [m/s]</b> |
|---------------------------------------|---------------|--------------|-----------------|----------------|
| <b>Validation</b>                     | 55.62         | 304.84       | 81.36           | 0.52           |
| <b><math>\sigma</math> Validation</b> | 0.43          | 0.09         | 0.05            | 0.21           |
| <b>AO1</b>                            | 55.72         | 304.81       | 81.35           | 0.52           |
| <b><math>\sigma</math> AO1</b>        | 0.36          | 0.08         | 0.04            | 0.18           |
| <b>AO2</b>                            | 56.02         | 304.75       | 81.32           | 1.72           |
| <b><math>\sigma</math> AO2</b>        | 0.23          | 0.05         | 0.03            | 0.68           |
| <b>AO3</b>                            | 55.77         | 304.80       | 81.35           | 0.73           |
| <b><math>\sigma</math> AO3</b>        | 0.33          | 0.07         | 0.04            | 0.32           |
| <b>AO4</b>                            | 56.04         | 304.75       | 81.31           | 0.81           |
| <b><math>\sigma</math> AO4</b>        | 0.15          | 0.03         | 0.02            | 0.30           |
| <b>AOA</b>                            | 56.14         | 304.73       | 81.30           | 1.79           |
| <b><math>\sigma</math> AOA</b>        | 0.06          | 0.01         | 0.01            | 0.54           |
| <b>AOB</b>                            | 97.87         | 298.01       | 76.52           | 1.79           |
| <b><math>\sigma</math> AOB</b>        | 0.06          | 0.01         | 0.01            | 0.54           |

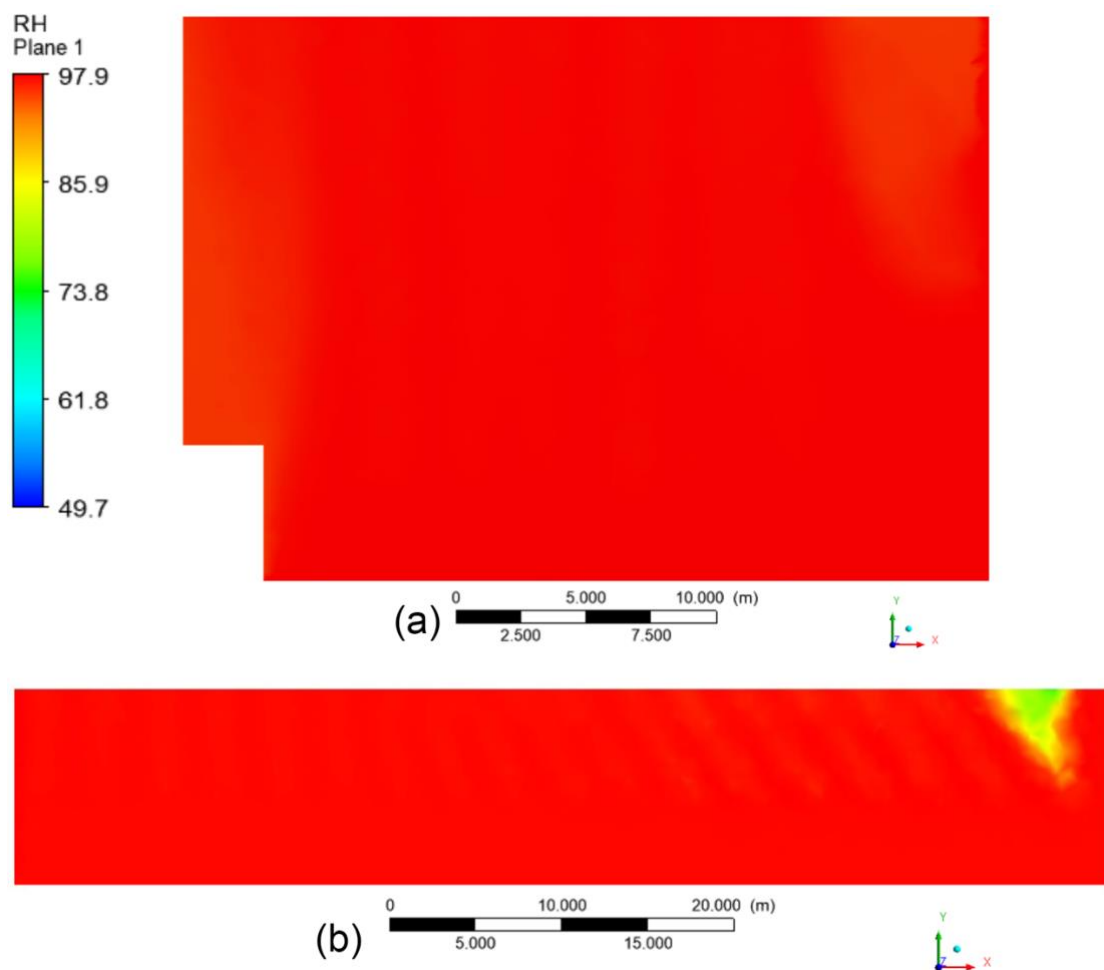


Figure 27. XY plane results for RH, Z=1.2m. (a) optimization AOB, Facility I, (b) optimization BOB, Facility II. Font - author.

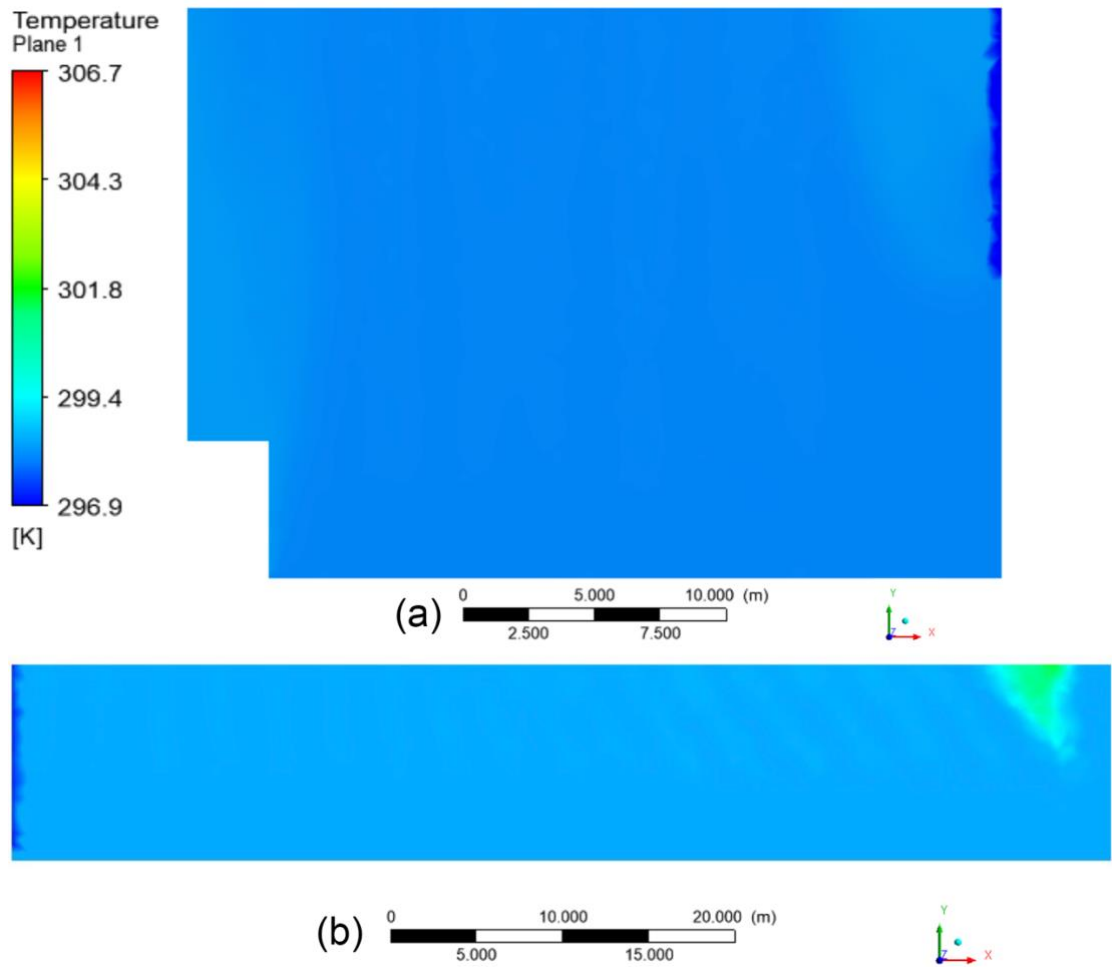


Figure 28. XY plane results for T, Z=1.2m. (a) optimization AOB, Facility I, (b) optimization BOB, Facility II. Font - author.

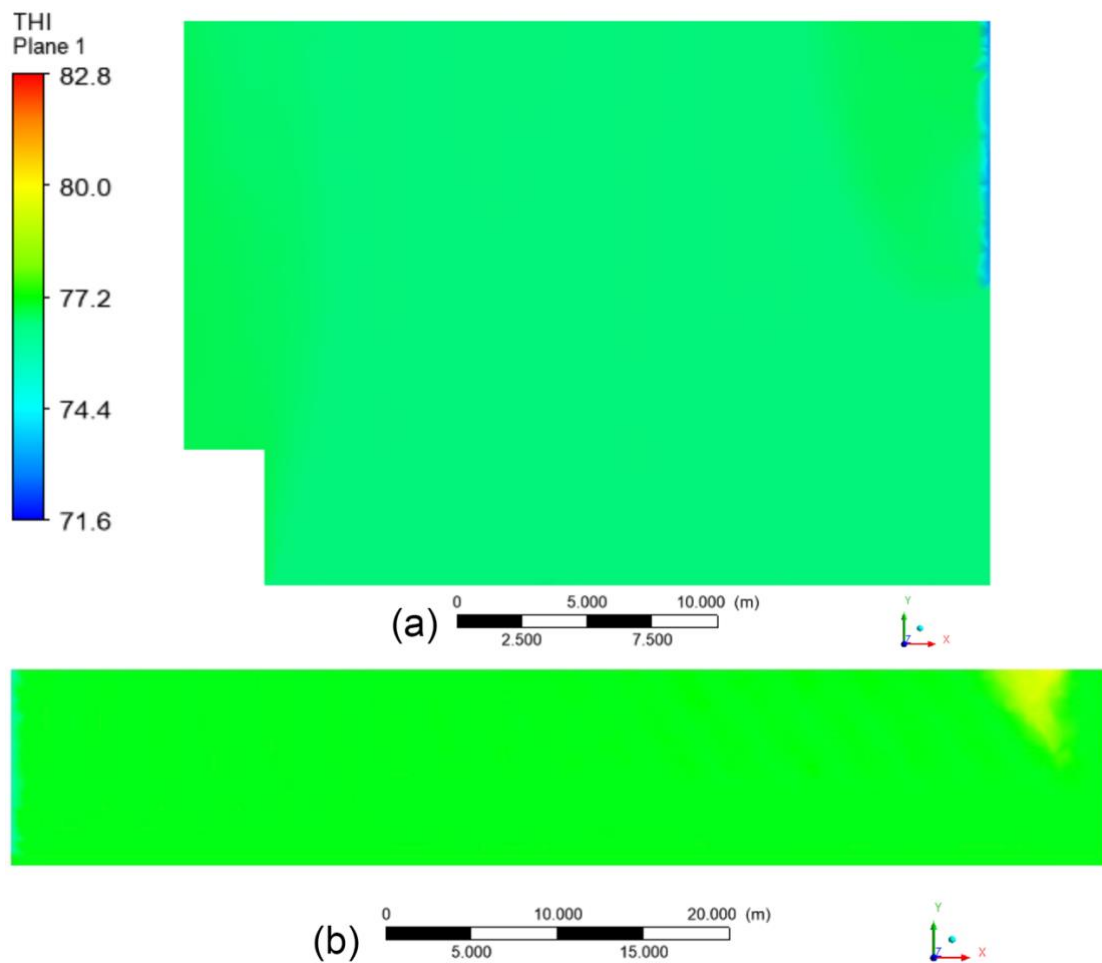


Figure 29 XY plane results for THI, Z=1.2m. (a) optimization AOB, Facility I, (b) optimization BOB, Facility II. Font - author.

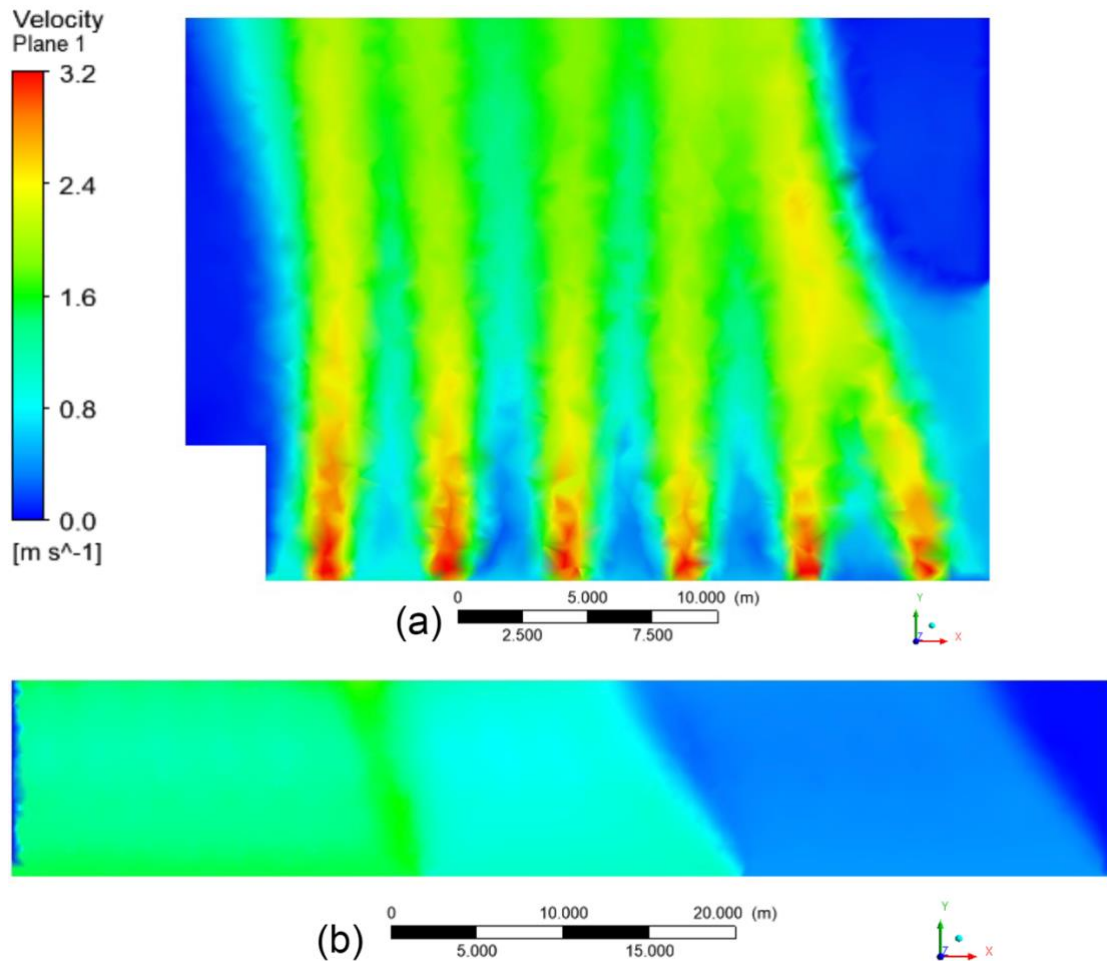


Figure 30 XY plane results for velocity,  $Z=1.2m$ . (a) optimization AOB, Facility I, (b) optimization BOB, Facility II. Font - author.

For Facility II, the modifications in the roof (Table 23) represented a decrease of  $0.01^{\circ}C$  for THI and the improvement in the conditions of  $0.06 m s^{-1}$  in ventilation, in this case, a recommendation is included to clean the surrounding area to improve the air flow, the distances and areas are shown in Table 21. Comparing the installation of the fans in the lower and upper part of the windows, the first one (BO2) shows better conditions for THI, decreasing THI by  $0.01^{\circ}C$  and improving by  $0.27 m s^{-1}$  compared to validation. BO4 shows a decrease in THI of  $0.05^{\circ}C$  and an increase in  $0.29 m s^{-1}$  in airflow. BOA does not need fans and THI decreases by  $0.05^{\circ}C$  and increases  $0.4 m s^{-1}$  in airflow.

For BOB, the evaporative cooling system shows a decrease in THI of  $5.58^{\circ}C$  and an increase in  $0.4 m s^{-1}$  for air velocity. BOB is the best option calculated to improve comfort, according to the results shown in Table 23. Figure 34 shows the area involved in the evaporative cooling system. Installing a ventilation system close to the height of the pig will improve the air renewal rate, complying with the recommendations, the evaporative cooling system decreased the THI values, improving comfort. It is possible to combine an evaporative system with the increase in height, these are the most representative changes according to the results.

Table 23. Average results for RH, T, THI, and v for optimization, Facility II.  
Font - author

|                                       | RH [%] | T [K]  | THI [°C] | v [m/s] |
|---------------------------------------|--------|--------|----------|---------|
| <b>Validation</b>                     | 50.63  | 306.50 | 82.67    | 0.45    |
| <b><math>\sigma</math> Validation</b> | 0.29   | 0.07   | 0.04     | 0.23    |
| <b>BO1</b>                            | 50.72  | 306.48 | 82.66    | 0.51    |
| <b><math>\sigma</math> BO1</b>        | 0.27   | 0.06   | 0.03     | 0.30    |
| <b>BO2</b>                            | 50.73  | 306.47 | 82.66    | 0.72    |
| <b><math>\sigma</math> BO2</b>        | 0.17   | 0.04   | 0.02     | 0.70    |
| <b>BO3</b>                            | 50.65  | 306.49 | 82.67    | 0.75    |
| <b><math>\sigma</math> BO3</b>        | 0.30   | 0.07   | 0.04     | 0.77    |
| <b>BO4</b>                            | 51.01  | 306.41 | 82.62    | 0.74    |
| <b><math>\sigma</math> BO4</b>        | 0.09   | 0.02   | 0.01     | 0.35    |
| <b>BOA</b>                            | 51.03  | 306.40 | 82.62    | 0.85    |
| <b><math>\sigma</math> BOA</b>        | 0.05   | 0.01   | 0.01     | 0.41    |
| <b>BOB</b>                            | 97.67  | 298.34 | 77.09    | 0.85    |
| <b><math>\sigma</math> BOB</b>        | 0.07   | 0.01   | 0.01     | 0.41    |

The average results of all proposals for Facility I are shown in Figure 31 for  $v$  and Figure 32, for THI. It is possible to appreciate the improvement in THI and speed using evaporative cooling and ventilation systems. Those areas were chosen to encourage lateral airflow at the inlets, changing the boundary conditions in both cases.

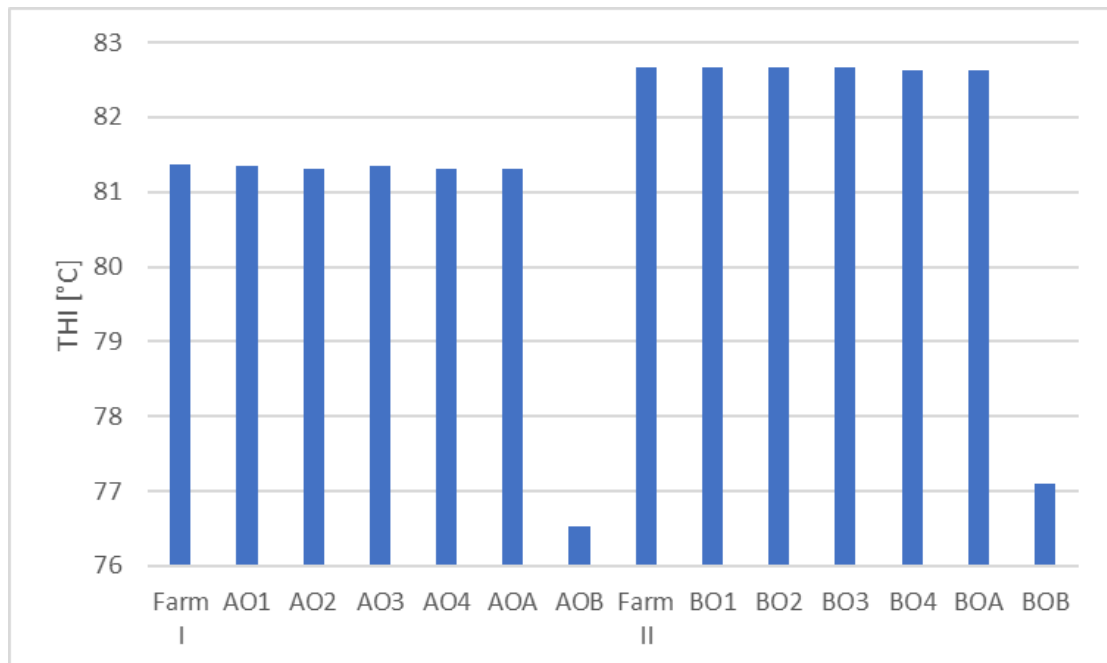


Figure 31. Average results for THI [°C] in the improvement proposals for the two facilities selected. Font - author.

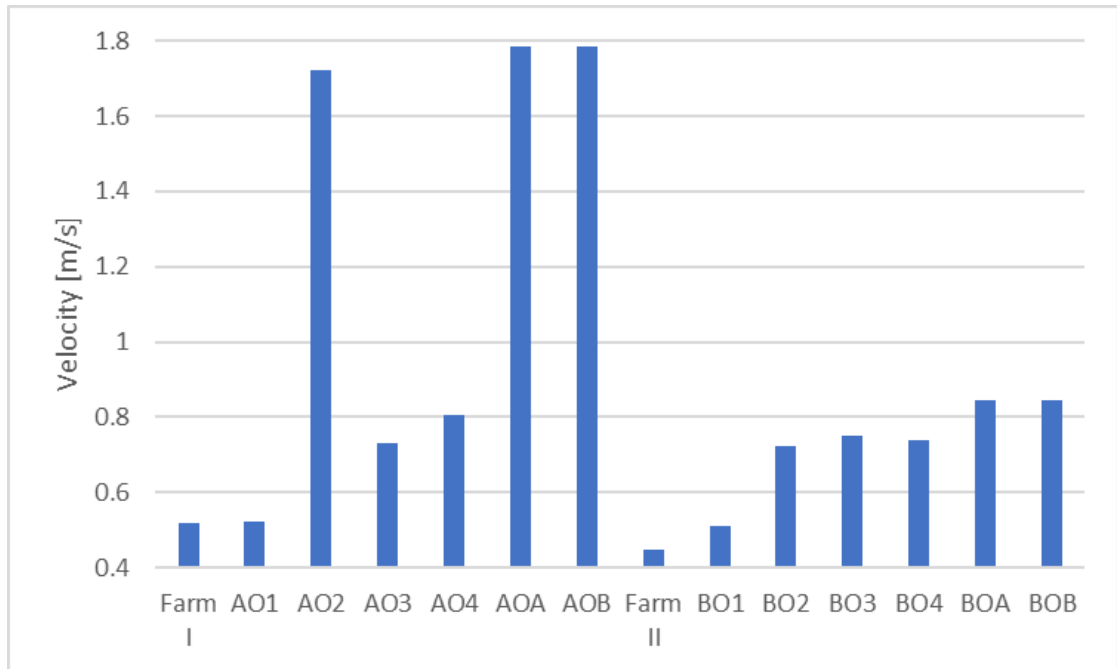


Figure 32. Average results for air velocity [m/s] in the improvement proposals for the two facilities selected. Font - author.

Based on the information obtained by the evaporative cooling calculation, the corresponding nebulizers were located in each structure. In Facility I, the installation of a total of 40 meters of pipe with nebulizers is proposed, and a total of 68 meters in Facility II. Both systems have a water collection system, allowing it to return to the pump room in order to recycle the water resource. The scheme of the system design is shown in Figure 33 for Facility I and in Figure 34 for Facility II.

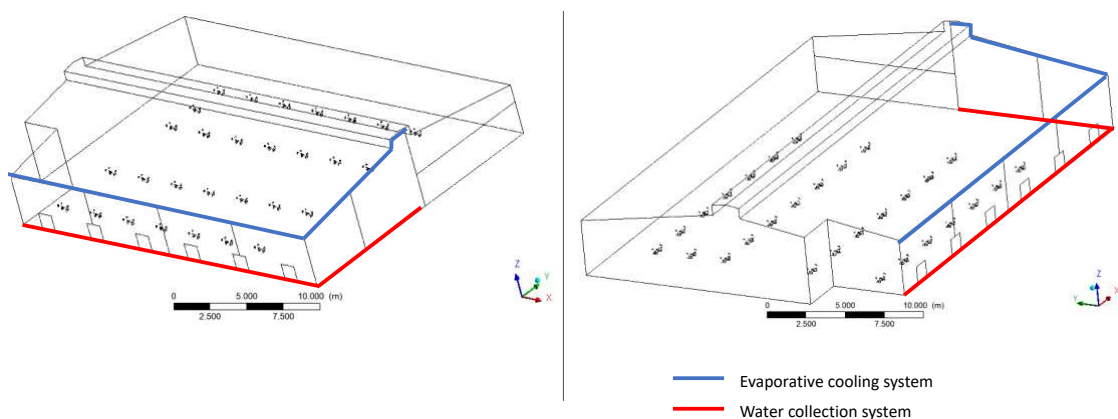


Figure 33. Evaporative cooling area involved for Facility I, AOB. Font – author.

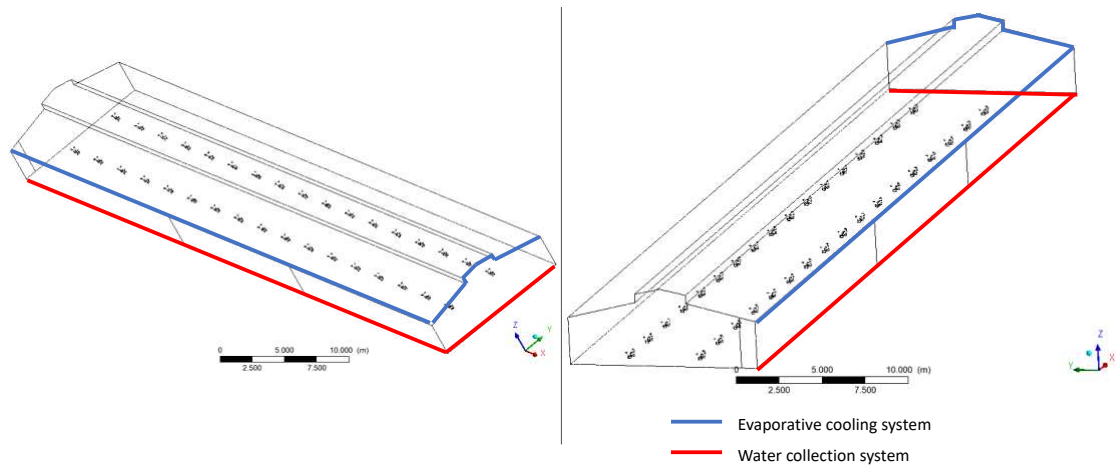


Figure 34. Evaporative cooling area involved for Facility II, BOB. Font – author.

Figure 35 shows the behavior of the use of humidity on the roof and floor for AOB, the THI index decreases, improving comfort for the pigs, in comparison with no use of humidity where THI is greater than the use of humidity.

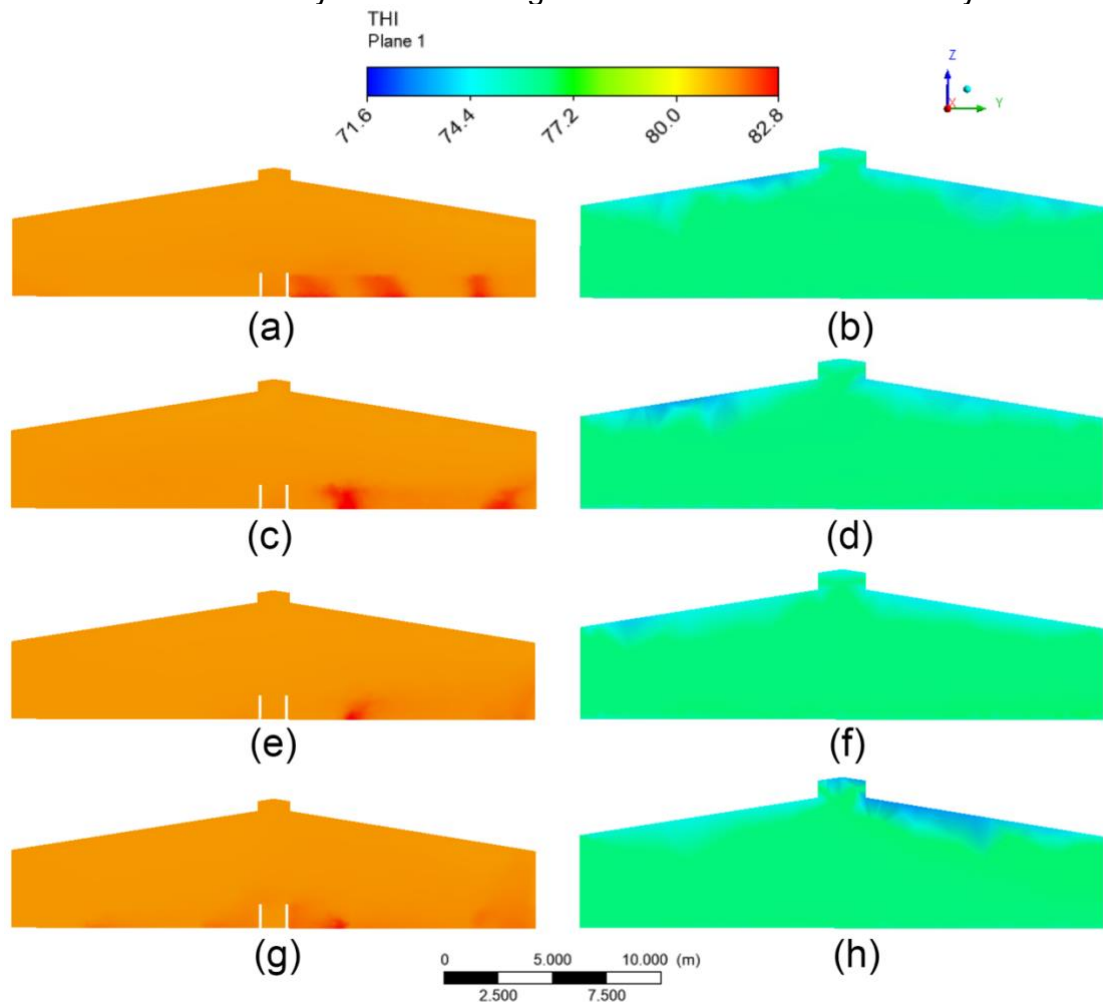


Figure 35. YZ plane for Results for THI using evaporative cooling systems in Facility I, ceiling and floor, optimization AOB. (a) no modifications, X=6m. (b) AOB, X=6m. (c) no modifications, X=12m. (d) AOB, X=12m. (e) no modifications, X=18m. (f) AOB, X=18m. (g) no modifications, X=24m. (b) AOB, X=24m. Font - author.

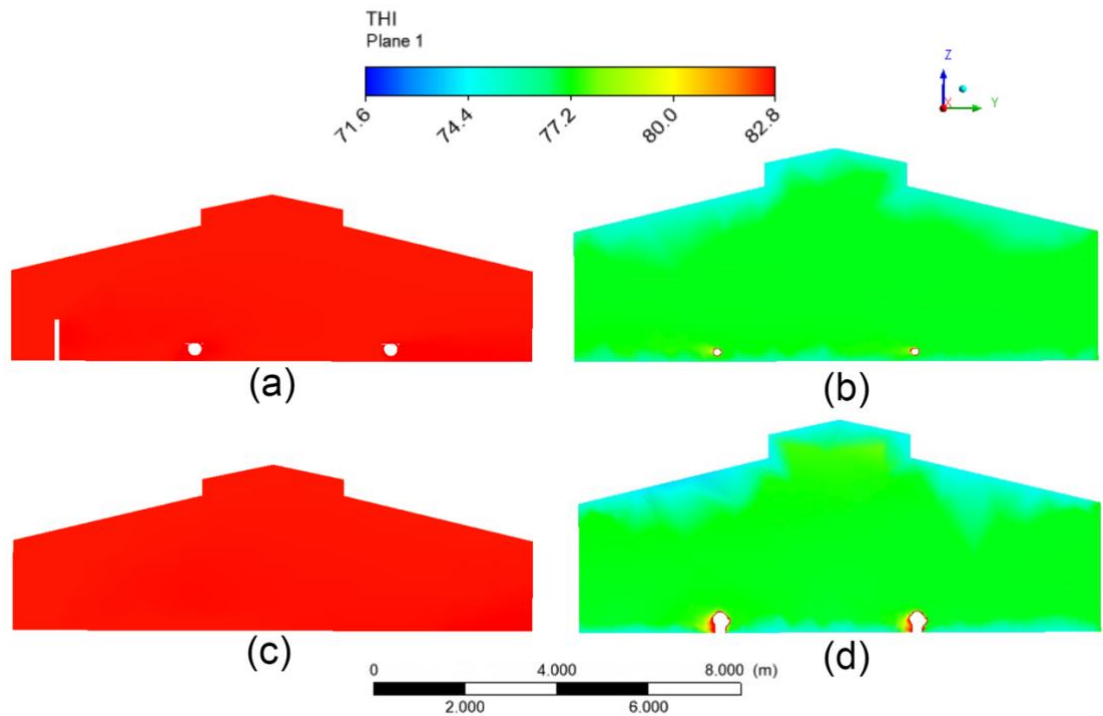


Figure 36 shows the behavior of the use of humidity on the roof and floor, the THI index decreases, improving comfort for the pigs, in comparison with the non-use of humidity where THI is greater than the use of humidity.

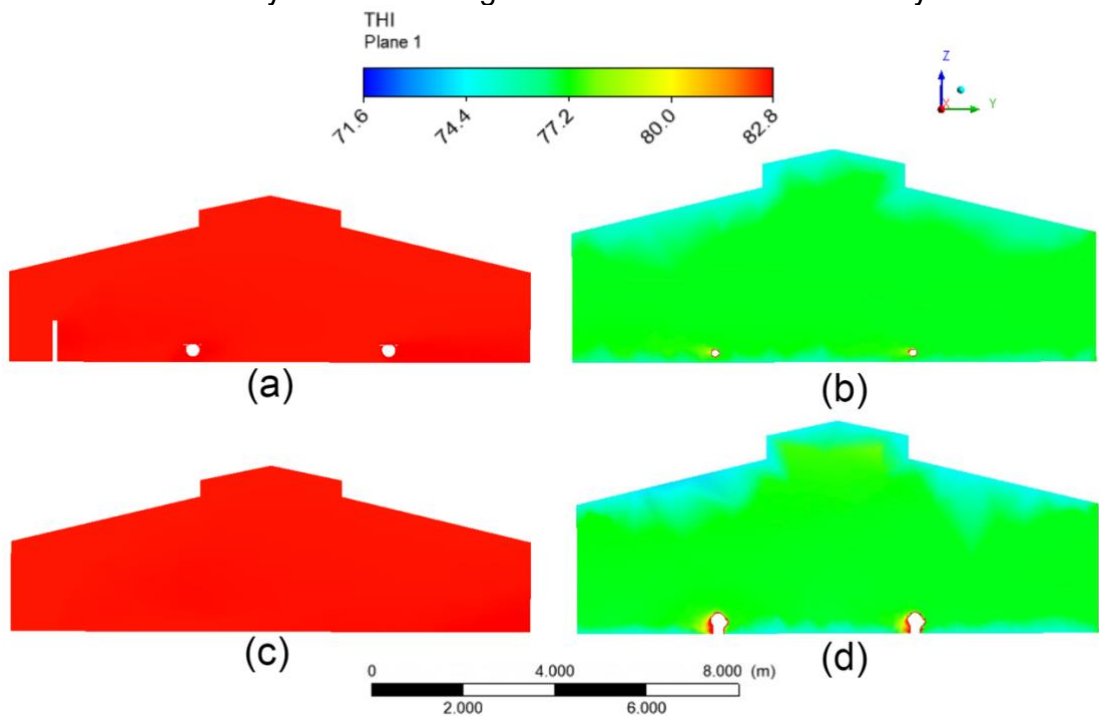


Figure 36. Results for THI and using evaporative cooling system for ceiling and floor, optimization BOB. (a) no modifications, X=12m. (b) BOB, X=12m. (c) no modifications, X=48m. (d) BOB, X=48m. Font - author.

## 5. CONCLUSIONS AND RECOMMENDATIONS

The thermal environment and air flow of three naturally ventilated facilities in different thermal floors and typological conditions for production, in tropical climates, were

evaluated by means of CFD. The validation was developed by comparing the data obtained in the field with CFD where the data were statistically acceptable in the studied variables (T, RH, THI and  $v$ ).

The study resulted in the need to improve two of the facilities Facility I and Facility II in accordance with the results previously obtained for THI. For these installations, the result of the proposals resulted in a reduction of THI 4.84 °C and an improvement of the airflow in and 0.65 m / s for Facility 1 (Table 22) and 5.58 °C in THI and 0.40  $m s^{-1}$  of air flow for Facility II (Table 23). These results allow to improve the climatic conditions inside the facility for the animals, reducing the alarms for comfort. An appropriate environment represents better conditions for production, providing producers with tools to improve processes and profitability. The most representative changes in the facilities are evaporative cooling to reduce the THI and the change in dimensions to promote air flow within the facilities.

According to the results obtained by the proposed modification, Figure 31 shows that the evaporative cooling system is the best improvement to decrease THI, compared to making changes in the materials or dimensions of the facilities in both cases. To improve the air flow, for Facility I, calculating only one ventilation system can significantly improve the air rate inside the installation, for Facility II it is possible to improve the air speed only by changing the dimensions. As a recommendation, Facility I can implement an evaporative cooling and ventilation system and for Facility II only change the total height without changing the materials, in both cases.

This study is considered a pioneer in terms of the use of CFD to study constructive typologies for pork production, additionally, there are many more constructive typologies, which can be developed through this software, in the same way to make more proposals and combinations. of the improvements proposed in this text. The number of pigs used can also be varied with CFD to know how the internal conditions vary and what would be the maximum capacity allowed that does not activate comfort alarms.

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