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IMPACTS OF CROSS VENTILATION APPLIED TO AN EMERGENCY SHELTER IN A CONTAINER, THROUGH COMPUTER SIMULATIONS WITH BIM-BES INTEGRATION

Impactos da ventilação cruzada aplicada a abrigo emergencial em contêiner, por meio de simulações computacionais com integração BIM-BES

Impactos de la ventilación cruzada aplicada a refugios de contenedores de emergencia, mediante simulaciones computacionales con integración BIM-BES

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ABSTRACT

With the increase in the occurrence of disasters and, consequently, the growing demand for emergency housing, there is a need for a quick and viable construction solution. Containers are suitable in this context due to their modularity, which addresses these requirements. Despite the advantages, the use of containers for housing requires attention in terms of thermal performance, since they have a steel shell, which favors heating inside the module. Studies have shown that the use of thermal insulation in the composition of walls and ceilings helps to improve indoor thermal conditions, but it is not enough to provide adequate levels of performance. Therefore, this study proposes analyzing different cross-ventilation approaches as a solution to be combined with insulating materials to improve the thermal performance of this type of housing. For this purpose, computational fluid dynamics simulations were carried out for five modules with different window layouts. Two software packages were used for simulations, which allowed analysis of the distribution of ventilation and air temperature. The results indicate that the most efficient strategy was the configuration with conventional front openings combined with elevated openings on the opposite walls. In addition, the use of two software packages made the analysis comprehensive and reliable.

RESUMO

Com o aumento da ocorrência de desastres e, consequentemente, a crescente demanda por habitações emergenciais, surge a necessidade de uma solução rápida e viável de construção. Os contêineres se encaixam neste contexto visto que sua modularidade atende essas necessidades. Apesar das vantagens, o uso de contêineres para habitações exige atenção quanto ao desempenho térmico, uma vez que este possui a envoltória composta por aço, o que favorece o aquecimento no interior do módulo. Estudos comprovam que o uso de isolantes térmicos na composição das paredes e teto auxilia na melhoria da temperatura no interior, mas não é suficiente para proporcionar níveis adequados de desempenho. Neste sentido, este estudo propõe analisar diferentes abordagens de ventilação cruzada como uma solução a ser associada aos materiais isolantes para melhorar o desempenho térmico desse tipo de habitação. Para isso foram realizadas simulações computacionais de dinâmica dos fluidos para cinco módulos com diferentes disposições de janelas. Para as simulações foram utilizados dois softwares, o que permitiu que fossem realizadas análises acerca da distribuição da ventilação e da temperatura do ar. Por meio dos resultados, é possível concluir que a estratégia mais eficiente para esse tipo de habitação foi do módulo com aberturas frontais convencionais e aberturas altas nas paredes opostas. Ainda, o uso de dois softwares tornou as análises amplas e confiáveis.

RESUMEN

Con el aumento de la ocurrencia de desastres y, en consecuencia, la creciente demanda de viviendas de emergencia, se requiere una solución de construcción rápida y viable. Los contenedores encajan en este contexto, ya que su modularidad satisface estas necesidades. A pesar de sus ventajas, el uso de contenedores para vivienda requiere prestar atención al rendimiento térmico, ya que cuentan con una carcasa de acero que favorece la calefacción dentro del módulo. Estudios demuestran que el uso de aislamiento térmico en la composición de paredes y techos ayuda a mejorar la temperatura interior, pero no es suficiente para proporcionar niveles adecuados de rendimiento. En este sentido, este estudio propone analizar diferentes enfoques de ventilación cruzada como solución para combinar con materiales aislantes y mejorar el rendimiento térmico de este tipo de vivienda. Para ello, se realizaron simulaciones de dinámica de fluidos computacional para cinco módulos con diferentes disposiciones de ventanas. Se utilizaron dos programas de software para las simulaciones, lo que permitió analizar la distribución de la ventilación y la temperatura del aire. Los resultados muestran que la estrategia más eficiente para este tipo de vivienda fue el módulo con aberturas frontales convencionales y aberturas altas en las paredes opuestas. Además, el uso de dos programas de software permitió que los análisis fueran amplios y fiables.

INTRODUCTION

Currently, the world's population has been affected by inclement weather resulting from natural and man-made disasters that generate profound social impact, where countless families lose their homes and are exposed to situations of vulnerability (Zanella et al., 2017). A disaster is defined as any adverse event, whether man-made or of natural origin, which causes damage and economic and social losses (Castro, 2019).

Kobiyama et al. (2006) point out that natural disasters such as floods, hurricanes, droughts, and landslides are severe phenomena that result in damage and socio-economic losses. These occurrences have become an increasingly present topic in everyday life (Asito, 2022). With the intensification of armed conflicts, climate change and poverty around the world, millions of people are forced to leave their homes in search of better conditions (Carbonari, Librelotto, 2022). Zanella et al. (2017) state that the growing vulnerability caused by situations of severe destruction, leaving families displaced and vulnerable brings the need to implement emergency shelters to minimize this impact.

According to the United Nations High Commissioner for Refugees - UNHCR (2020), emergency housing is a fundamental solution for restoring personal security, dignity and self-sufficiency in crisis. Housing classified as emergency seeks to serve the portion of the population affected by disasters, whether climatic or social in nature. These events result in high demand and rapid execution of temporary housing. In these cases, shelters are built using available materials and techniques, the primary purpose of which is to provide life support without creating external dependencies (Anders, 2007).

The definition of the type of shelter involves aspects such as the complexity involved in decision-making, the spatial context and the place of insertion, which justifies the inadequate functioning of some of the models developed (Feres, 2014). The Handbook for Emergencies, created by the United Nations Refugee Organization, proposes important parameters for the structures of shelters and camps for refugees, offering minimum standards for this type of housing to guarantee the quality of these structures (The Un Refugee Agency,2007).

Current solutions for emergency shelters prioritize structures that are portable, removable, and quick to assemble (Sperb, 2011). Furthermore, the design of these shelters seeks to ensure aspects of the occupants' dignity, such as privacy and comfort. Junqueira's (2011) study outlines two guidelines for housing the homeless: the use of transportable shelters that are previously constructed and stored, and the adaptation of existing buildings, such as schools, gymnasiums and churches, used as collective shelters for immediate emergencies.

Bellomo et al. (2025) point out that to effectively meet the demands and contingencies of disaster-affected populations, it is important to combine interventions that consider the social and cultural backgrounds of the groups, the economic and technological characteristics of the states in demand, as well as the local workforce. Among the processes of operating and building emergency shelters, rational planning plays a crucial role in disaster situations, which often aim to minimize execution time and optimize layout (Sun & Chu, 2024).

Containers represent a promising solution in this context, as they are modular structures that can be linked together, reducing the time it takes to make them and therefore facilitating mass production. In addition, thousands of containers are stored and unused, making it important to find a way to reuse these materials. The growing demand for more efficient housing and buildings makes the reuse of containers an effective solution, since they are recyclable, durable, resistant and can generate savings for the sector (Martins et al., 2023). In line with sustainable needs, the use of containers as modular construction is becoming popular, making their use in housing a promising alternative (Costa et al., 2023).

Modular buildings are those in which the composition of various environments is made up of three-dimensional modules, which are pre-assembled in manufacturing centers and delivered to the construction site for installation on permanent foundations (Kamali, Hewage, Sadiq, 2019). In addition to reducing execution time, this construction method shows good results in reducing the amount of waste generated and mitigating greenhouse gas emissions compared to traditional methods (Ghaffarianhpseini et al., 2020).

In this way, modular architecture has interesting benefits for implementation, such as emergency housing. Containers used as modular housing have great potential to meet emergency demand, as they are a sustainable solution of obvious and simple quality (Haque, Aman, Mohammad, 2022). The use of modules for housing purposes brings not only advantages but also challenges.

Llorent et al. (2022) emphasize that emergency shelters often lack ventilation and use inadequate materials, resulting in uncomfortable temperatures, which can compromise the health and well-being of the occupants. Furthermore, Tru, Rigg, and Kin (2024) show that the lack of adequate separation between groups of shelter occupants leads to uncontrolled access, increasing vulnerability to violence. Kalil and Ali (2021) point out that poor spatial planning and the location of emergency housing areas also make them inefficient.

The study by Conzatti et al. (2022) reveals through a review of literature that housing affects the health of occupants in various ways and by various factors such as overcrowding, thermal extremes, humidity, indoor air pollution, and mold. The same study also shows that although there are guidelines on population density, there are few standards for adequate ventilation and temperature.

In view of the concern to improve the thermal aspects of this type of housing, the use of containers for this purpose raises a problem. The module's shell is made of steel, a material with high thermal transmittance, which causes a significant increase in internal temperature. Several authors have proposed a way of mitigating this problem by adding layers of insulating materials to the steel envelope.

Elrayies (2017) evaluated the performance of container-based buildings in a hot and humid region with four different thermal insulation materials: rock wool, wool, closed-cell spray polyurethane foam (ccSPF), and straw, concluding that ccSPF is a compatible solution, especially as a heater in winter. Costa et al. (2023) simulated materials associated with the envelope of an emergency container dwelling and selected the composition of the module with the best thermal performance. Like these, other authors have studied insulating materials applied to the container and analyzed the thermal results.

In addition to the difficulties encountered in emergency shelters, the intensification of the global warming phenomenon has led to concern about the thermal conditions of buildings due to rising air temperatures, especially in hot climates. Since one of the problems presented using containers for housing is the overheating of the structure, it is important to seek, in addition to insulating materials, strategies that can reduce the internal temperature of this type of housing.

In this context, bioclimatic strategies are presented as a set of active or passive techniques that are implemented in the architecture of the building to contribute to reducing the energy consumption of a building (Agugliaro et al. 2015). Also, bioclimatic design makes use of environmental resources to improve the internal and external thermal comfort of a building (Daemei, Eghbali, Khotbehsara, 2019). For bioclimatic approaches to be effective, they need to be aligned with both the project and the climatic conditions in which the dwelling in question will be located (Elaouzi & El Fadar, 2022).

This study proposes associating the cross ventilation bioclimatic strategy with the Costa et al. (2023) module to increase the results in terms of air quality, in terms of intensifying the ventilated area, and reducing the air temperature inside this type of building.

The movement of air from openings in facades and its movement inside the building defines natural ventilation, which can occur through the difference in temperature between inside and outside, or through the action of the wind (Lukiantchuki et al., 2016). Cross ventilation proposes an improvement in the quality of internal ventilation by means of openings on opposite facades that distribute the layers of air by the difference in pressure caused by the openings (Projeteee, 2020).

Seeking to find strategies that can improve thermal performance, the use of computer analysis helps to predict the results of a strategy to be adopted, even before it is used. Computer simulations allow a range of design variants to be compared, providing a better understanding of the consequences of design decisions, optimizing and increasing the effectiveness of processes (Augenbroe, 2001).

Mata et al. (2024) explain that BIM (Building Information Modeling) makes it possible to design geometry and model the information on the properties of materials and building elements, and interaction with BES (Building Energy Simulation) makes it possible to evaluate the performance of buildings through thermo-energy simulations. BIM-BES integration allows thermo-energy analyses to be optimized through workflow with data transfer, aiding the project decision-making process (Vaz, 2022).

There are different methods for analyzing the performance of natural ventilation, among them the computational fluid dynamics (CFD) model, a solution in a BES environment that provides air pressure field distributions and turbulence parameters for internal and external spaces, through the appreciation of a set of differential and partial equations (Chen, 2008). In this way, computer simulations can predict the results of the proposed strategy.

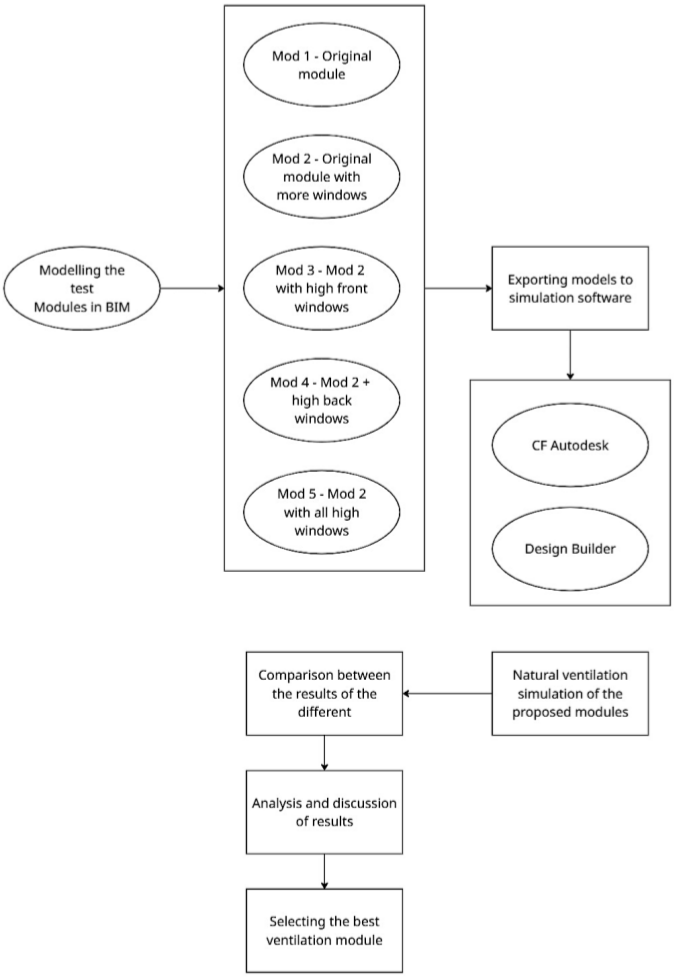
The aim of this research was therefore to verify the best arrangement of air inlet and outlet openings in a containerized emergency shelter, to validate the bioclimatic strategy of cross-ventilation as a way of improving the thermal performance of this type of building.

The proposal makes an important contribution by investigating the use of the cross-ventilation bioclimatic strategy as a way of improving the thermal performance of emergency housing built from containers, a construction technique that is growing in all contexts of crisis or housing shortages. In this way, this study stands out for applying computer simulation tools to analyze air behavior in different container shelter configurations, seeking viable solutions. The study proposes practical and effective interventions that enhance natural ventilation by reducing dependence on mechanical systems, promoting housing that is more suitable for use in emergency scenarios.

METODOLOGY

The methodology used for this study aims to evaluate the dynamics of natural ventilation inside a module intended for emergency housing in a container by means of computer simulations. To do this, modeling and analysis software will be used that allows the ideal representation of the physical conditions of the environment, to analyze the performance of the air flow for different window configurations in the module. This approach seeks to optimize the potential of natural ventilation as a passive strategy for improving thermal performance in emergency housing situations, where resources for artificial air conditioning are generally limited. It should be noted that no experimental measurements were performed to validate the software used. The focus of this study is to compare different architectural solutions regarding window layout, with the aim of identifying the most efficient configuration for air circulation between rooms (Figure 1).

Figure 1. The research methodology was structured according to the flowchart below



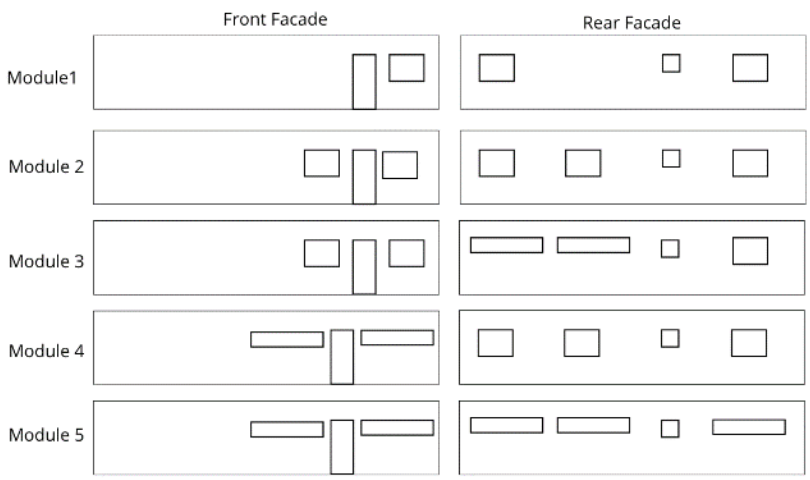
Source: Authors (2025).

The first stage consists of making a simplified model of the dwelling proposed in the study by Costa et al. (2023). This modeling represents the container to be tested in its original geometry, along with the simplification of complex geometric elements, such as the corrugated sheet metal of the external structure. The study by Vaz et al. (2024) proves that the simplification of geometry contributes significantly to the transfer of BIM\BES data. It shows that data such as the thermal properties of building components, as well as the geometry, are transferred at a higher rate when the geometry is simplified.

The wall structure was modeled using the "onion wall" method, which divides the original structure into layers of simple geometry, with the materials configured according to the originals, maintaining the thermal characteristics of each element that makes up the wall, resulting in the composition of a basic geometry. The analyses were carried out for five proposed container modules, differentiated by the number and characteristics of the windows (Figure 2).

Module 1 - Based on the model by Costa et al. (2023), without alterations.
Module 2 - Original model with the addition of one window on the front facade and one on the back facade, both in the living room/kitchen area.
Module 3 - Module 2 with the windowsills on the rear facade altered to 1.60m.
Module 4 - Module 2 with the windowsills on the front facade altered to a height of 1.60m.
Module 5 - Module 2 with the sills of all the windows changed to 1.60m.

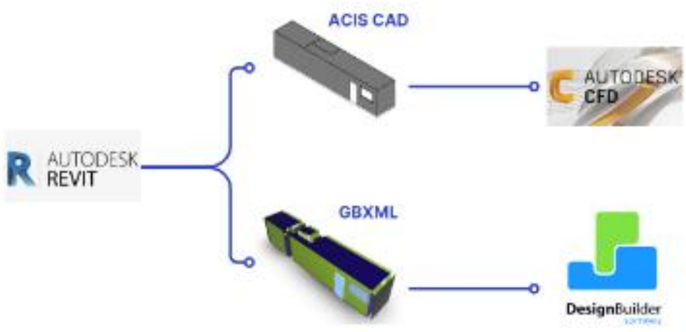
Figure 2. Module configuration in terms of openings



Source: Authors (2025).

The modeling was configured in Revit 2025 software and exported to the BES environment, represented by Autodesk CFD and Design Builder software, according to the flow in Figure 3.

Figure 3. BIM/BES workflow and interoperability



Source: Authors (2025)

The Autodesk CFD software reads files in the ACIS CAD format, which contains all the information about the three-dimensional modeling, making it necessary to configure the materials and their properties again, since this format does not contain this type of information.

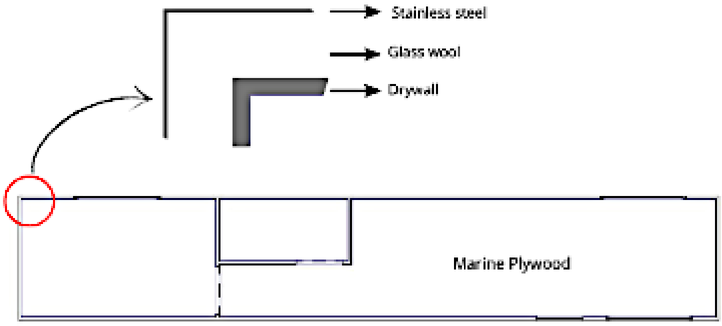
For the CFD Autodesk simulations, the envelope materials were configured based on the reference container in the study by Costa et. al (2023). Using the software database, materials like the base container were selected, and the thermal characteristics of these materials were adjusted. The envelope was made up from the outside in with stainless steel (304), glass wool, and drywall. The windows were configured with an aluminum frame and glass closure, and the external door and floor were made of naval plywood. The air inside the rooms was configured on the inside of the module as a variable fluid material. Table 1 shows the thermal characteristics relevant to the analysis, adjusted in Autodesk CFD, and Figure 4 shows the application of these materials in the module layers.

Table 1. Properties of the materials that make up the housing envelope configured in Autodesk CDF

Material	Thermal Conductivity (W/m.K)	Thermal Transmittance (W/m².ºC)
Stainless steel	55	21153,85
Glass wool	0,031	0,62
Drywall	0,35	19,44
Marine Plywood	0,12	4,00

Source: Costa et al. (2023).

Figure 4. Arrangement of the container materials in the Autodesk CFD



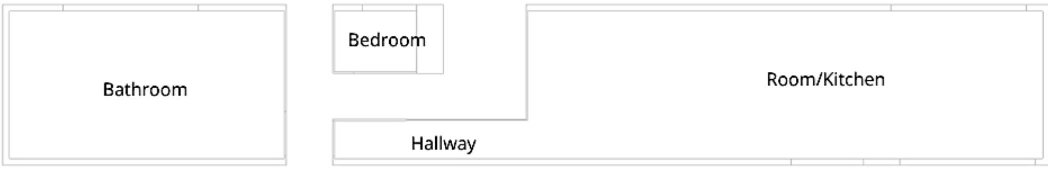
Source: Author (2025)

Autodesk CFD software enables analysis of ventilation turbulence and air temperature inside the module. As discussed above regarding the problem of high temperatures in containerized housing, the ventilation analysis was performed on a summer day with a maximum temperature of 37ºC, where the entire module was exposed to sunlight, with no shaded areas.

Design Builder imports files in the Green Building XML (gbXML) format, which stores and shares some of the building's properties between software, making it necessary to review the transported characteristics and adjust those not transported, just like in Autodesk CFD. According to Vaz et al. (2024), the interoperability process between Revit and Design Builder effectively transfers only the thermal characteristics of the roof, ceiling, windows, and floor components and wall materials need to be configured. For the analysis in this software, the natural ventilation model available in the program's database was adopted, which has pre-settings for the natural ventilation analyses for a residential building. The energy model, when inserted into Design Builder, is separated into surface layers (Figure 5), where each layer represents a zone of the model to be analyzed, so the container model was subdivided into three analysis blocks.

Design Builder only analyzes the turbulence of the ventilation inside the module, so it doesn't need to consider the external temperature settings.

Figure 5. gbXML module imported into Design Builder



Source: Authors (2025)

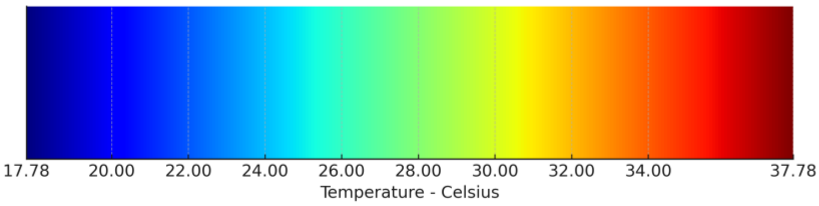
The purpose of using two software programs for the same type of analysis was to improve the visualization of the results and verify their reliability through analysis and discussion. For the analysis, the windows on the front facade were considered as air inlets, the windows on the back facade were considered air outlets, and the critical facade was north-facing front facade. Therefore, all the proposed modules were configured using the same variables and simulated in both software packages to analyze the results and select the module with the best ventilation.

RESULTS AND DISCUSSION

Autodesk CFD software provides visual results of ventilation in air masses, while Design Builder provides results in vectors. Therefore, to better understand the results obtained with the software, it was necessary to compare images from different angles due to the overlapping of both the masses and the vectors in different views. To interpret the following results, it is first necessary to analyze the characteristics of the images delivered by each of the software packages.

The air masses shown in the Autodesk CFD results display different colors within the module due to the temperature variation of the circulating air. Light/dark coloration represents temperature variation, with the most intensely colored masses representing the hotter temperatures. For a better understanding of the temperatures of the air layers, the color scale illustrated in Figure 6 will be used.

Figure 6. Scale for Autodesk CFD temperature analysis



Source: Authors (2025)

For the analysis of images obtained by Design Builder, the vectors' coloring is differentiated by wind speed. Figure 7 presents the legend used to associate color with wind speed. Therefore, for the Design Builder analyses, the vectors represented by dark blue tones are points where there is no air, light blue tones are regions with speeds close to zero, green and yellow vectors are areas with considerable ventilation, and orange and red vectors represent regions with intense speeds.

Figure 7. Design Builder analysis legend

Source: Authors (2025)

From the natural ventilation simulations, in each module proposed in this research, the results presented below were obtained.

1. Module 1

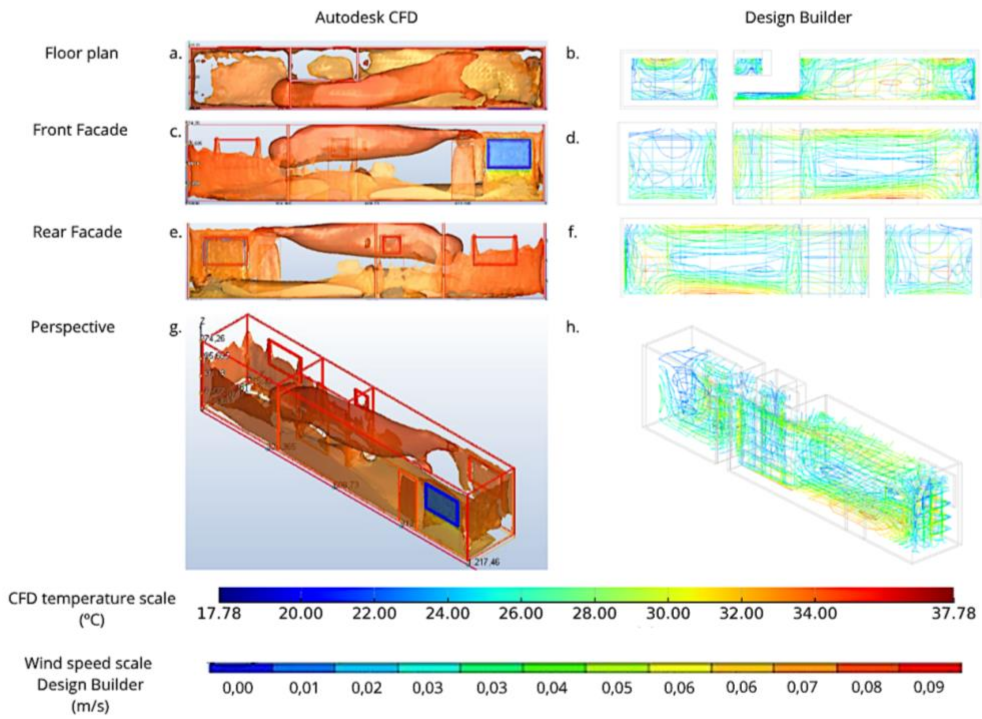
In Figures 8a and 8b, for the integrated living room/kitchen environment, both the current lines and the air masses are concentrated near the window openings and the dividing wall with the bathroom. In the central region of this room (Figures 8c, 8d, 8e, 8f) the layers tend to be positioned near the floor and ceiling, indicating a less dense ventilation gradient in the middle range.

In the hallway, as shown in Figures 8b, 8c, 8g, and 8h, there are many current and mass vectors, which characterize good ventilation along with its length. In relation to the bedroom, concentrations of air flow and masses are identified near the floor and perimeter walls (Figures 8a, 8d and 8g), with a significant reduction as they advance in height, until they disappear at heights above the windowsill (Figure 8c), which suggests that the air circulates mainly below 1.10 m in this environment.

In the bathroom, it is observed that air movement is also restricted to the lower regions and around the walls, as shown in Figures 8a, 8b and 8e, indicating low air renewal in the upper portion of the environment. The simulations developed in CFD Autodesk allow us to identify that the layers of air with higher temperatures tend to concentrate near the ceiling, moving from the living room/kitchen space towards the bedroom, infiltrating a small portion of this environment.

In general, the joint analysis of the figures indicates the formation of a hot air flow in the upper portion of the model, resulting from the imbalance in the air distribution caused by the location of the openings. This configuration generates an accumulation of air masses in the lower extremities of the environments and zones of low ventilation in the central areas. It is also worth noting the predominance of the reddish coloration of the air masses, which represent temperatures ranging from 34º to 37ºC.

Figure 8. Module 1 ventilation

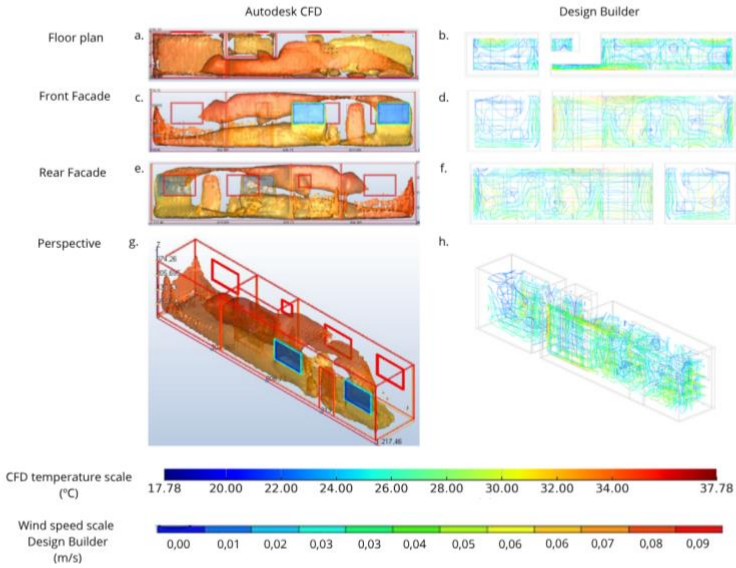


Source: Authors (2025).

2. Module 2 - Largest number of openings

For this simulation, two windows were added, one on the front facade and the other on the back, to assess the impact on the dynamics of natural ventilation. In Figure 9b, it is evident that the kitchen/living room division exhibits an increase in the presence of low-speed vectors in the central area compared to the reference module. The same regions can be observed in Figures 9c and 9g, as zones of rarefied flow. The corridor, meanwhile, maintains ventilation characteristics like those observed in the previous simulation, with good distribution of air flow along its length.

Figure 9. Module 2 ventilation



Source: Author (2025).

In relation to the bathroom, Figure 9a indicates that the air mass occupies almost the entire space but is concentrated in the area close to the floor, suggesting limitations in the upper layers. In the bedroom (Figures 9c, 9d, 9e, 9f), it is possible to see that air circulation also occurs predominantly below the windowsill, showing that even with the introduction of new openings, the vertical restriction of ventilation remains.

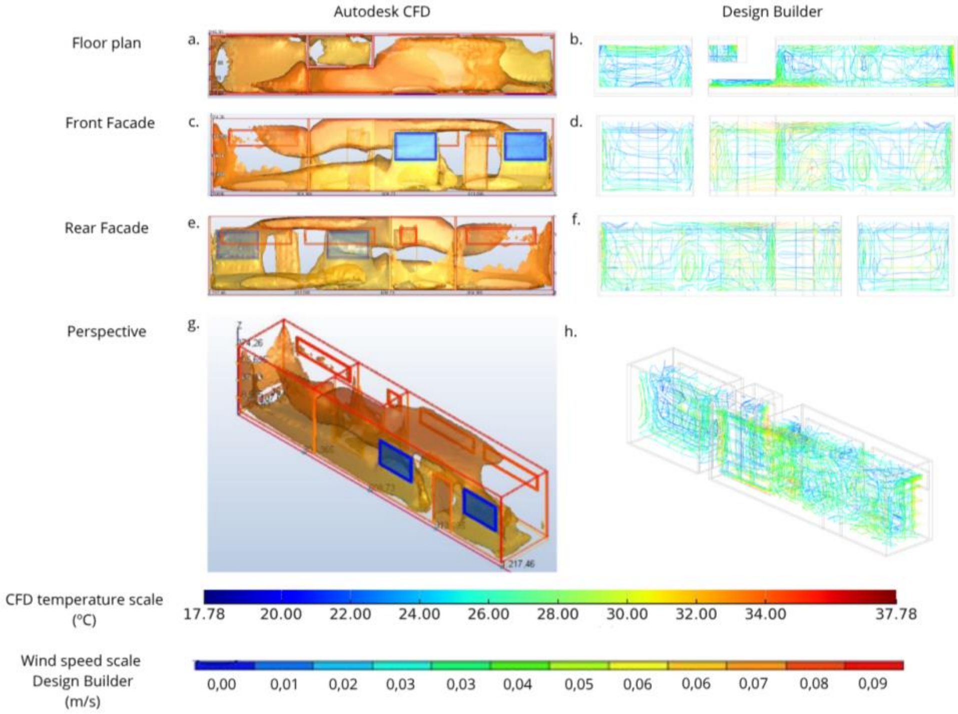
Regarding temperature, the layers of hot air at the top continue to be concentrated near the ceiling. However, unlike the reference module, there is a slight increase in the infiltration of this air towards the bedroom. In addition, there is a visual distinction between the tones of the layers: the top layer has a more intense color, indicating temperatures close to 37ºC, while the bottom layer, with a more yellowish tone, represents air with temperatures ranging from 32º to 34ºC. This stratification of the air reinforces the action of natural thermal convection, with hot air occupying the upper regions of the environment.

The analysis of Module 2 shows that the addition of openings in the front and back facades resulted in specific changes in the behavior of the air flow, especially in the living room/kitchen area, where a greater presence of low-speed vectors was observed in the central region. Although this redistribution suggests a slight expansion of the ventilated areas, no significant gain was observed in the vertical ventilation of the environment, since in both the bathroom and the bedroom the air movement continued to be concentrated in the lower areas, below the level of the windowsills. Although the intervention promoted small improvements in the horizontal distribution of ventilation, the effects on air renewal in the upper areas and on thermal homogenization are still limited.

3. Module 3 - Changes to the windowsills on the rear façade

For Module 3, the windowsills on the rear facade were changed to a height of 1.60 m above the floor. As can be seen in Figure 10a, the air mass in the living room/kitchen space occupies a significant portion of the space; however, in the upper right corner of the space, this mass is restricted to the areas closest to the floor (Figure 10e). In relation to the hallway and bathroom, no significant changes were observed in the distribution of air masses and velocity vectors (Figures 10a, 10b, 10c, 10f), since there were no changes to the openings in these spaces.

Figure 10. Module 3 ventilation



Source: Authors (2025).

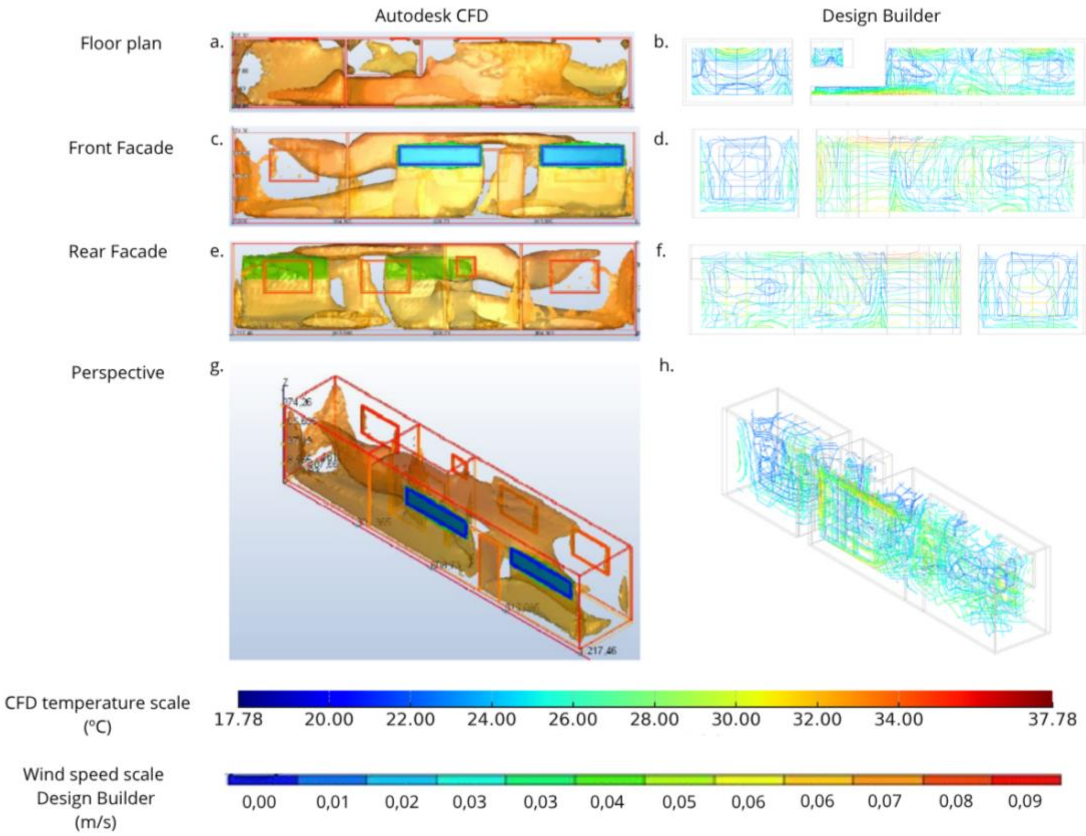
In the bedroom, in turn, there was an improvement in the distribution of the air layer according to the height, which was previously concentrated close to the floor. In Figures 10 (10c, 10d, 10e, 10f, 10g, 10h) it is possible to see a more extensive upper air layer than that presented in Module 1. Regarding the temperature, it is possible to observe that both the upper and lower layers are presented in lighter yellowish tones, indicating temperatures ranging from 32º to 34ºC, that is, a reduction in the temperature of the air circulating inside the module.

In general, the results obtained in Module 3 indicate a more balanced performance of natural ventilation performance compared to the previous modules, especially in the bedroom, where the elevation of the windowsill favored a better distribution of the air mass in height. The modifications regarding the openings allowed greater penetration of ventilation in the upper regions of the environment, contributing to the exhaustion of hot air. Furthermore, the uniformity in the color of the air layers, associated with the lighter tones, suggests a reduction in internal temperatures, indicating greater efficiency in dissipating accumulated heat. Although the corridor and bathroom environments did not show significant changes due to the maintenance of the original openings, the module showed an improvement in the quality of the air flow.

4. Module 4 - Changes to the windowsills on the front facade

For Module 4, the windows on the front facade were repositioned with the windowsill raised 1.60 m. As illustrated in Figures 11 (11a, 11b, 11g), the integrated living room/kitchen environment, the lack of ventilation in the upper right corner persists in relation to Module 1. On the other hand, the air masses are more evenly distributed, resulting in a reduction in areas of low ventilation. The corridor remained without significant changes in air dynamics, showing behavior like the previous simulations. In the bathroom, in turn, a reduction in air vectors and masses can be seen (Figures 11a and 11b).

Figure 11. Module 4 ventilation



Source: Authors (2025)

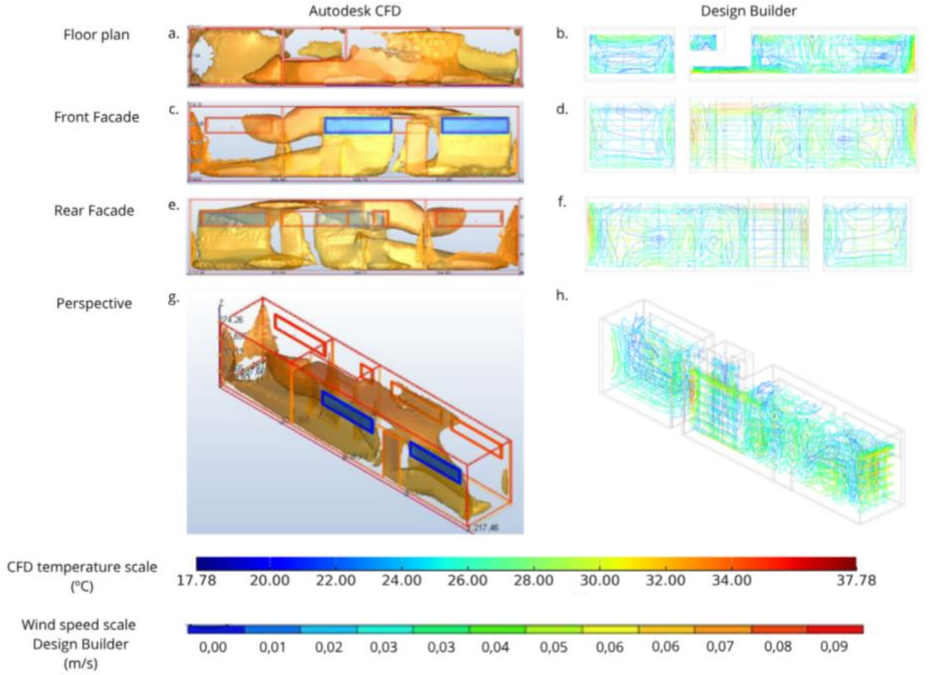
In the bedroom, it is possible to observe through Figures 11 (11c, 11d) that the upper air mass had a greater reach in relation to Module 1. In addition, the air layer close to the floor becomes larger and changes color, evidencing greater air movement in this region, as well as a change in temperature. Regarding the temperature, it is noted that the air masses are yellowish in tone, indicating that the temperature in this Module is between 32º and 34ºC. The findings suggest that there was also a reduction in air temperature.

Module 4 showed significant improvements compared to Module 1, especially in the rooms facing the front facade, where the windows were raised to a 1.60m windowsill. This modification contributed to a uniform distribution of air masses, reducing areas with little movement, especially in the living room/kitchen area. The bedroom also showed significant gains, with greater penetration of air mass in the upper part, indicating an improvement in air renewal. The corridor did not show a significant change in the arrangement of the air flow, but the infiltration of these layers into the bathroom was reduced. Regarding the thermal aspect, there was a clear reduction in the temperature of the internal air, reinforcing the potential of repositioning the openings to improve natural ventilation.

5. Module 5 - Changes to the windowsills of all windows.

For Module 5, all windows were configured with 1.60m windowsills. Figures 12 (12a, 12g) show an improvement in the distribution of ventilation for the integrated living room/kitchen space. Previously, the mass that was concentrated near the floor in Module 1 is now positioned closer to the ceiling and walls with openings. This new configuration favored ventilation of higher areas. There was a small reduction in the ventilation of the bathroom, as seen in Figures 11a and 11b. For the bedroom, a significant increase in the ventilated area can be observed, with the lower layer being distributed evenly throughout the space (Figures 11a, 11b) and the upper air mass reaching a greater range (Figures 11a, 11c and 11g).

Figure 12. Ventilation Module 5



Source: Authors (2025)

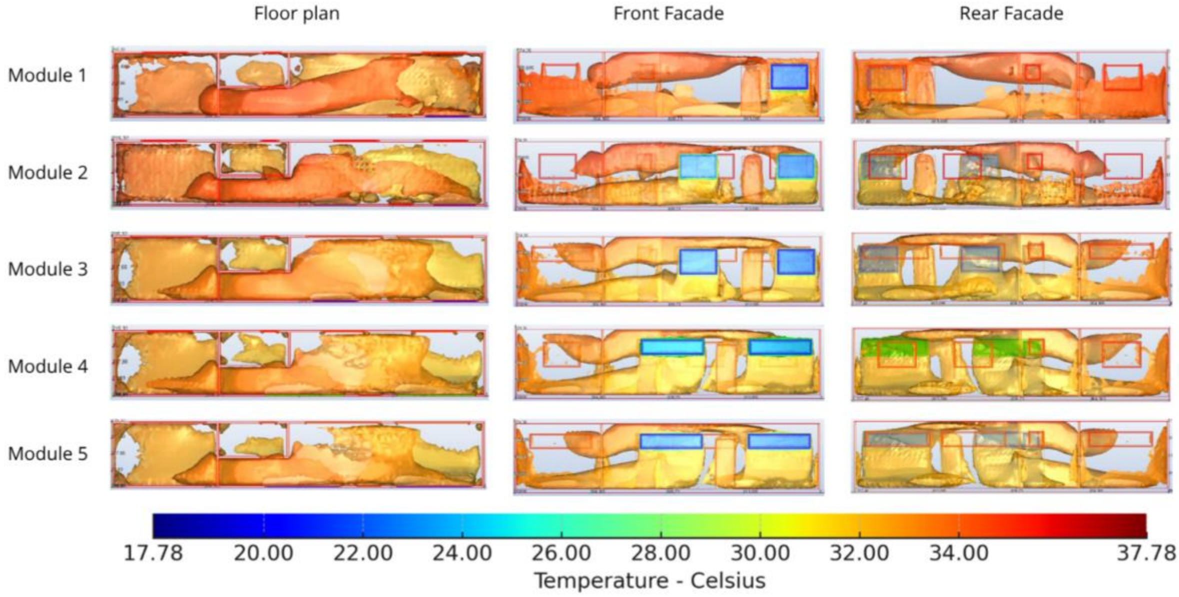
In terms of air temperature, the masses presented a variable temperature of 30º to 34ºC, as in simulations 3 and 4. In general, the elevation of the windowsill proposed in this Module promoted a redistribution of air masses in the environments, especially in the living room/kitchen and bedroom environments, where the upper masses obtained greater reach.

6. Definition of the module with the best ventilation

Based on the natural ventilation analysis performed for each proposed module, it is possible to conclude that the results obtained by CFD Autodesk provide a comprehensive and effective visual reading of the air dynamics in the different environments of the container. Two factors were considered to define the module with the best ventilation: coverage of ventilated areas and lower temperature of the air circulating through the module, factors that will be analyzed in comparison to the container adopted as a reference for this study (Module 1).

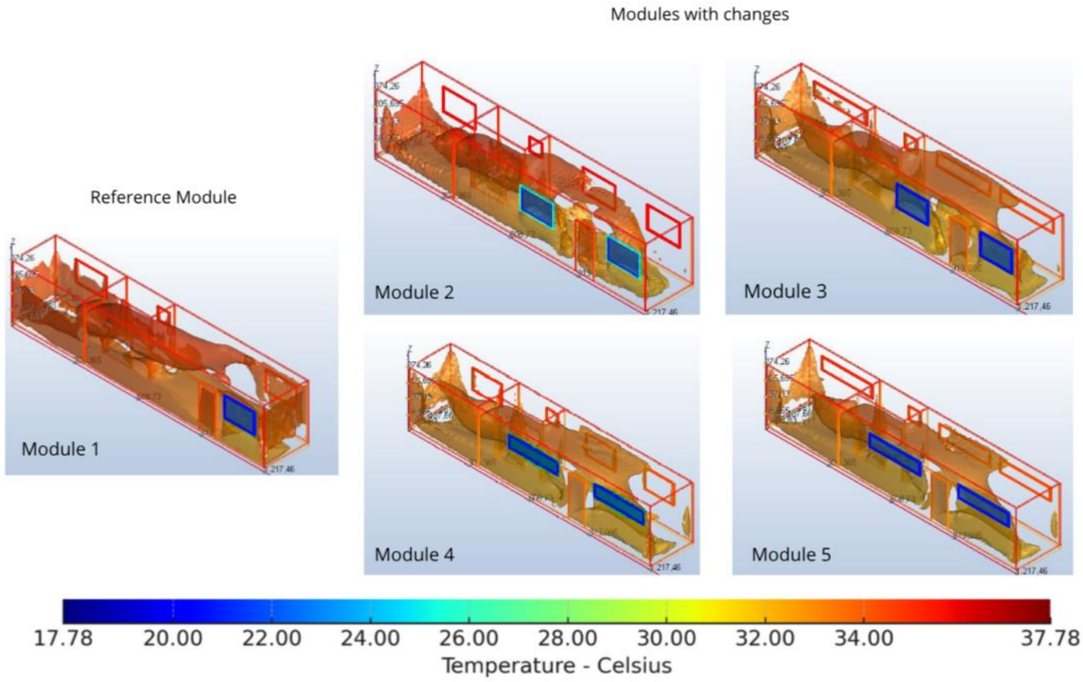
Figures 13 and 14 show a comparison of the CFD Autodesk results for the Module configurations with all the proposed changes. Regarding the coverage of ventilated areas, it is possible to observe that Module 3 stands out for presenting a wider distribution of air masses, both in the lower and upper layers, close to the ceiling. Regarding air temperature, a cooling trend is observed from Module 3 onwards, coinciding with the change in windows with high sills (1.60 m), which is evidenced by the predominance of lighter colors in the simulations.

Figure 13. Comparison of results in Autodesk CFD view



Source: Authors (2025).

Figure 14. Comparison of results in Autodesk CFD perspective



Source: Authors (2025)

Based on simulations performed by Design Builder, Module 3 demonstrated better performance in terms of air movement and turbulence. The images indicate a distribution of effective wind vectors for the occupied areas, especially in low and medium areas. The change in the windowsills of the rear facade contributed to intensifying internal circulation, moving the air layer to higher regions. This configuration indicates the most potential for air renewal and dispersion, making Module 3 the most efficient among the models compared in terms of internal air dynamics.

Table 2 presents the ventilation results as a function of layer height and air temperature, based on the results obtained from the comparison of each Module in relation to Module 1. In this way, it is possible to analyze in a simplified way the defining factors for selecting the module with the best performance.

Table 2. Comparison of results in relation to Module 1

Module	Opening Configuration	Ventilation	Air Temperature
Module 1 (Reference)	Standard windows - 1.10m windowsill	Living room/Kitchen – Predominantly in low layers Hallway – Upper hot air duct Bathroom - Limited to the floor and surrounding walls Bedroom - Limited to the floor and surrounding walls, below 1.10m	Predominant reddish color; temperature between 34º and 37ºC
Module 2	Openings on opposite walls 1.10m windowsill	Living room/Kitchen – Predominantly in low layers Hallway – Upper hot air duct Bathroom – Larger coverage close to the floor Bedroom – Limited to the floor and surrounding walls, below 1.10m, greater infiltration portion of the upper layer	Predominant reddish color; temperature between 34º and 37ºC
Module 3	Rear windows with 1.60m sill	Ventilation flows greater than in the previous ones. Living room/kitchen – Distribution between the layers, low, medium, and high. Hallway – Low, medium, and high flow. Bathroom – Greater coverage close to the floor. Bedroom – Better infiltration of the upper layer	Significant reduction in temperature. Temperatures are between 32º and 34º C
Module 4	Front windows with 1.60m sill	Living room/Kitchen – Distribution between layers, low, medium, and high Hallway – Low, medium, and high flow Bathroom – Air mass recess close to the floor Bedroom – predominant close to the floor better infiltration of the upper layer	Significant reduction in temperature. Temperatures between 32º and 34º C.
Module 5	All windows with 1.60m sill	Slight recess in ventilation for all rooms	Significant reduction in temperature. Temperatures between 32º and 34º C

Source: Authors (2025).

Considering the two factors for selecting the best performing module in terms of ventilation, it is possible to conclude that Module 3 presents the best results.

FINAL CONSIDERATIONS

The results obtained demonstrated that interoperability between BIM-BES environments is an efficient process, as it shortens processes with previous modeling and configurations regarding material properties, validating the statement by Vaz (2023). It is also observed that the use of different software for the same analysis allows for the understanding and reliability of the results. Although the results are delivered in different formats, Design Builder and CFD Autodesk achieved results that were consistent with each other.

Although both software programs used in the simulations offer significant contributions to the study of natural ventilation, each has specific limitations that must be considered when analyzing the results. Design Builder offers a greater variety of configurations related to architectural modeling, such as defining the type of building, occupancy schedules, climatic conditions regarding the location, among other parameters. However, its simulation of natural ventilation is limited to vector results regarding air distribution and velocity.

On the other hand, Autodesk CFD offers a more comprehensive approach, allowing analysis of turbulence, distribution, and temperature of air layers. However, this software is restricted in defining architectural parameters. Its settings focus mainly on the properties of materials and the boundary conditions of the simulated environment, limiting the fidelity of the model in relation to the real use of the built space. Therefore, the choice between tools should consider the focus of the study in question, recognizing that none of them, in isolation, may be capable of representing all the variables involved in the thermal performance and natural ventilation of a building.

Through graphical analyses, it is possible to broadly evaluate the trajectory of the air inside the container module. Design Builder's vector results represent a greater amplitude in terms of wind speed, starting from speed 0 to higher speeds (in this study up to 0.09 m/s), and Autodesk CFD reproduces this result as empty for regions with speeds close to 0, making the visualization more understandable.

While Design Builder presents vector results that only cover ventilation turbulence, Autodesk CFD associates this same result with the temperature of the air masses, which allows for a more complete evaluation of results. It can be concluded that the visual results delivered by Autodesk CFD are simpler to analyze and easier to understand.

Regarding the arrangement of the openings for the validation of the cross-ventilation strategy, proposals were made for modifications regarding the number and height of the windows. By adopting a greater number of openings, an improvement in the coverage of the ventilated area can be observed. By adopting a raised windowsill, there is a reduction in the ventilation temperature inside the module. By associating these two decisions, it is possible to obtain the desired result.

The cross-ventilation strategy proposes an improvement in the internal ventilation of an environment due to the difference in pressure between the opposite openings (RODRIGUES, 2008). Modules 3 and 4 present similar results, as both have openings with a 1.10 m sill on one wall and a 1.60 m sill on the opposite wall. The difference between the two is in the direction of the air inlet and outlet. Corroborating Rodrigues (2028), Module 3 presented a larger ventilated area and a greater reduction in air temperature, since the air inlet has larger openings and the outlet has higher openings.

In addition to the concern with the materials used in the envelope, which play an important role in the thermal insulation of this type of building, by associating the cross-ventilation strategy it is possible to enhance these results. In this way, it can be observed that passive bioclimatic strategies can be used to improve the thermal performance of emergency housing in containers.

To expand the understanding of the behavior of natural ventilation in emergency housing in containers, future research can explore the performance of natural ventilation in different types of climates with varying levels of occupancy. Another line of research with potential exploration is the incorporation of complementary bioclimatic strategies into sustainable and energy-efficient projects for this type of building.

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