The role of complex airflow simulation tools for overheating assessment of passive houses

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Abstract. Passive Houses are characterized mainly by construction concepts that greatly reduce energy usage during the winter, but that can lead to significant overheating during the hotter summer days. Since in the Passive House concept thermal comfort during the summer mainly relies on natural ventilation to provide indoor cooling, the importance of airflow modeling tools for overheating prediction needs to be investigated. This research analyzes the effect of simplifications commonly made in airflow modeling techniques on the overheating assessment of Passive Houses by collecting measured data and calibrating a thermal model with a Passive House case study. Utilizing the calibrated model, a standalone Building Energy Model (BEM), BEM coupled with an Airflow Network Model (AFN), and BEM coupled with an AFN supported by the wind pressure coefficient values obtained from Computational Fluid Dynamics (CFD) simulation were created. The outcome of each modeling approach was then compared against each other. Results showed that the default infiltration and natural ventilation input values commonly utilized in literature, when compared to those obtained from either the AFN or AFN+CFD, are significantly overestimating the natural ventilation potential of Passive House buildings, resulting in a lower number of overheating hours (39.9% decrease) and inaccurate overheating evaluation outcomes. Therefore, the paper concludes that the use of at least an AFN is necessary when estimating the overheating hours of Passive Houses.

1. Introduction

The building sector alone accounts for approximately 40% of the world's annual energy consumption [1]. From this percentage, as much as 60-70% of the building energy consumption is used to maintain the indoor space thermally comfortable [2]. With the goal of providing thermal comfort while reducing the energy demand for heating and cooling, the concept of Passive Houses was born in the 1980s, and it is now known to reduce the heating needs of buildings by a factor of 10 [3]. The European Passive House Institute (PHI) set heating and cooling demand threshold of 15 kWh/m² each, and five key passive design principles were established as the foundation of the standard. These design principles are high thermal insulation, airtight envelope, elimination of thermal bridges, high-performance windows and ventilation heat recovery [4]. The application of the Passive House standard to newly constructed dwellings, mainly those located in Europe, is considered an important approach to assist countries achieve the first indicative milestone of the Energy Performance of Buildings Directive (EPBD) goal of 30% energy demand reduction by 2030 [5].

Due to heat retention being the principal focus of these strategies, its construction approach allows mainly natural ventilation as means of removing heat and regulating internal air quality within its buildings. It successfully led to a substantial reduction on heating demand during the winter; however,
overheating during the summer became a well-documented issue in new homes and existing stocks throughout the entire European region [6-8]. In response to the increasing demand for Passive Houses, research regarding its present and future thermal behavior has become more frequent and dynamic building simulations became more often used in overheating prediction. Still, it is unclear whether current research considers the effect of different modeling methodologies, especially for airflow phenomena, when analyzing the overheating risk of a Passive House during the summer.

First, this paper selected existing research conducted in European countries such as Portugal, UK, France, Denmark, Sweden, Spain, and Italy to perform a literature review and analyze the methodology that each author is employing when performing an overheating analysis. Afterward, since the effect of different airflow modeling approaches on the results of the overheating assessment of Passive Houses was a relevant topic identified as not yet fully addressed by current literature, this study will compare the results obtained by BEMs with distinct representations of airflow, determining what level of simplicity a model can precisely predict overheating hours.

2. European Passive House standard research – past tendencies and current status

Literature dealing with Passive Houses explored mainly technological and financial conditions, such as economic viability [9, 10], energy performance [11, 12] and optimal operation [13]. As it is possible to notice from these research topics, the first stage of exploration was mainly focused on demonstrating and disseminating the idea of superior energy efficiency that Passive Houses had when compared to standard buildings. At this period, little attention was given to subjects such as the applicability of the standard to different climates, prediction of indoor thermal performance, indoor air quality, and resilient design to climate change.

With the development of more intuitive building energy modeling software packages and the acknowledgment of the energy efficiency of Passive Houses, research interests shifted. Researchers and practitioners started to widely utilize dynamic building energy simulations to investigate indoor thermal comfort, and the availability of measured data obtained from the first batch of Passive Houses built a few years prior allowed them to compare their simulated values to the measured ones. More recently, with growing concerns regarding climate change, experiments regarding the future performance of Passive Houses began [14].

While many of these studies have different objectives, in all of them natural ventilation plays a fundamental goal in the output of the research. Yet, the current Passive House overheating assessment methodology utilized in the vast majority of the papers reviewed are solely based on the BEM model, where infiltration and ventilation rates are assumed as arbitrary inputs. Figueiredo et al. [8] utilized a constant total airflow rate of 0.6 h\(^{-1}\) for each thermal zone throughout the entire summer and concluded that “summer comfort can be achieved by only resourcing passive improvements, without any active cooling system”; McLeod et al. [14] chose an infiltration rate of 0.035 ac/h and an airflow rate of 30 m\(^3\)/pp.h and concluded that “careful attention must be paid to the design assumptions and assessment criteria used to evaluate future overheating risks”. And that “in urban contexts, the possibilities of purge ventilation through opening windows may be limited or non-existent.” Hidalgo et al. [6] utilized a total air change rate of 0.7 h\(^{-1}\) during all the summer period to replicate natural ventilation when windows are open, while Nemecek and Kalousek [15] went further and created two ventilation profiles: 4-5 h\(^{-1}\) for overnight ventilation and 0.1 h\(^{-1}\) during the day.

Most of the other papers reviewed followed similar trends, where natural ventilation is acknowledged as a fundamental system to provide cooling during the summer, but the airflow rate value is either not mentioned in the paper or is given an assumed value without literature support. This shows that although the need to utilize the coupled model has been sufficiently demonstrated for naturally ventilated buildings, the current overheating assessment is solely based on the BEM model; an examination of the BEM model adequacy for overheating assessment is necessary.

3. Methodology

The main objective of this paper is to determine which modeling method is the most appropriate to predict overheating in Passive Houses that rely on natural ventilation for cooling during the summer. Specifically, to define if the BEM alone is sufficient to properly evaluate overheating risks, or if a more
advanced modeling method is necessary to capture actual airflow phenomena. Consequently, the research methodology was divided into three stages: Model inputs, where all the information regarding the case study and indoor measured data was be obtained, building energy simulation, where the model inputs are analyzed and included within each modeling approach to produce results, and overheating analysis, where the results of each simulation method are utilized to analyze overheating, and its outcome is compared to each other. The change in airflow modeling within the same case study allowed the evaluation of the advantages and shortcomings of each modeling approach in the context of overheating analysis of a Passive House and may serve as a guideline for the overheating assessment of other models built around similar context.

3.1. Case study building
This research has been carried out primarily by utilizing the energy model of the Fiorita passive house, a multi-story apartment building located within the Mediterranean climate of the city of Cesena, Italy (figure 1). The monitored apartment is located on the top floor of the building and sensors measuring the indoor conditions (air temperature, relative humidity, CO2 concentrations, and contact temperatures) were installed in the bedroom of the building. The monitoring process is more thoroughly explained in [16]. All the thermophysical properties of the building façade are publicly available in the building certification granted by the Passivhaus Institut [17]. The airtightness was tested according to EN ISO 9972 Standard [18] and the number of air changes per hour (ACH) for infiltration at 50Pa was $n_{50} = 0.41 \text{ h}^{-1}$. The building provides all necessary cooling/heating and ventilation through a mechanical ventilation with heat recovery (MVHR) system, and a centralized variable refrigerant flow (VRF) system served by an air-to-air heat pump. All building properties are summarized in table (1).

![Figure 1. Fiorita passive house outdoor view and surrounding context [16, 19].](image-url)
## Table 1. Fiorita passive house materials and HVAC summary.

| Basement floor/ floor slab | U-value (W/m2-K) | Design airtightness at 50Pa (ACH) | Mechanical systems |
|---------------------------|------------------|-----------------------------------|--------------------|
| Exterior Walls            | 0.185            | 0.119                             | 0.095              |
| Roof                      | 0.095            | 0.6                               | 0.41               |
| Glazing                   | 0.6              | Dynamic                           | Ventilation with eff. specif. heat recovery 91% |
| BEM Model                 | 0.41             | Dynamic                           |                    |
| Coupled Model             | Dynamic          |                                    |                    |

### 3.2. Energy model and calibration

The entire building was modeled using Rhinoceros 3D version 6.34 and the analyzed flat simulated with Grasshopper plugins Ladybug and Honeybee version 1.1.0 (figure 2). Since the neighboring flats are assumed to have a similar indoor experience, they were all added in the model as context geometry and all walls and floors from the simulated flat in contact with these apartments were added as adiabatic surfaces.

Given that all the construction material thermophysical properties (conductivity, specific heat, thermal and solar absorptance) are available in the Passivehaus certification, most of the thermal model uncertainty is related only to the building operation, which cannot be eliminated even in late design stages. A Mechanical Ventilation with Heat Recovery (MVHR) system with maximum flow rate of 230 m³/h and thermal efficiency of 90% was added in conjunction with a Variable Refrigerant Flow (VRF) system to provide heating/cooling whenever necessary to keep the indoor temperature within the range of 19-28°C. All occupant behavior (occupancy schedule, setpoints temperatures, lighting and equipment loads, etc.) was derived from the US Dept. of Energy’s Commercial Reference Buildings [20] and adapted to better represent numbers found in passive houses. TMYx weather data for the municipality of Forli, with hourly weather data available through 2018, was used in all simulations for a better representation of a recent typical meteorological year scenario in Italy [21].

![Figure 2. Model created using Rhinoceros 3D and Grasshopper using the Ladybug tools plugin.](image)

The entire model, including all material parameters, occupant behavior and HVAC systems, was tested and calibrated by comparing the simulated results with measured data obtained with sensors located in the bedroom. Figure 3 shows the calibration results for the summer and shoulder seasons, which demonstrates fairly accurate accordance with the measured temperatures. To quantify the efficacy of the calibration process, a root-mean squared error (RMSE) was also performed for the entire duration of the simulation. The results showed an average error of 0.948°C, implying that the model is reliably representative of the case study.
3.3. Thermal model, Airflow network model and CFD analysis

To accurately measure the impact of airflow modeling when performing an overheating assessment, the calibrated thermal model was then modified to remove all mechanical systems, basically becoming a free running building where natural ventilation becomes the only source of cooling. By performing the analysis this way, the importance of proper airflow modeling is emphasized while the results of the study become more applicable for other passive houses with varying mechanical systems. For the thermal model, instead of the mechanical systems providing cooling, natural ventilation was implemented. Since the thermal model is only based on heat balance principles, design airflow rates are required as inputs to consider the effect of infiltration and natural ventilation into the building loads. For infiltration, the value obtained from the Blower Door Test of 0.41ACH was used as default value, while 2.5ACH was used for ventilation, which is considered a reasonable value commonly used in simulations [22]. To represent some form of demand-controlled ventilation, the design flow rate was also connected to the fractional occupancy schedule of the room.

In contrast with the thermal model, the airflow network (AFN) model can dynamically simulate airflow every timestep by calculating the total pressure difference between two air nodes. Firstly, the pressure of each node is calculated according to Equation 1 and then, by applying the Bernoulli’s equation for each air flow linkage, the total pressure difference including the static and dynamic pressures as well as the influence of stack effect is calculated [23].

\[ m_i = \frac{AP_{i}}{\mu} \]

where \( m_i \) = air mass flow rate, \( \mu \) = air viscosity, and \( C_i \) = flow coefficient

Since the AFN model utilizes the same multi-zone nodes created by the thermal model to perform these calculations, coupling between the thermal model and the AFN model can be easily incorporated into the building simulation workflow. On the other hand, due to its inclusion, another layer of assumptions is also added into the model. This includes not only occupant behavior related to windows opening, but other input parameters such as flow exponent, leakage area, discharge coefficient, and wind pressure coefficients. Flow exponent and discharge coefficient are parameters that have a clear range of acceptable values between 0.5 and 0.75 [24]. For infiltration and wind pressure, both the Air Infiltration and Ventilation Centre (AIVC) and ASHRAE Handbook of Fundamentals 2001 provide effective leakage area (ELA) and wind pressure coefficients data for rectangular low-rise buildings with flat or pitched roofs and without any kind of wind-blocking elements [25, 26]. For this model, single-sided and buoyancy driven natural ventilation strategies were used and the windows control strategy has been modeled according to the temperature difference between the indoors and outdoors (\( T_{in} > T_{out} \)). To reflect infiltration, the total area of each façade element of the building is multiplied by the ELA and then inputted into EnergyPlus to represent the relationship between pressure, airflow
and the building façade.

For the CFD analysis, Eddy3D version 0.3.8.0, a Grasshopper plugin that servers as an interface for the simulation engine BlueCFD was utilized to model the area surroundings of the Fiorita Passive House and obtain more accurate wind pressure coefficient values (figure 4). Yearly average wind speed was utilized as baseline and wind directions in a 45-degree interval were used to calculate the pressure on the external façade and to obtain more representative Cp values of the building façade. The results were averaged over each façade area and then used as an input in the AFN model in EnergyPlus.

![Figure 4. Fiorita passive house surroundings simulated using CFD.](image)

4. Results and discussion

This section will investigate the choice between all three modeling techniques, a thermal model with the specification of airflow rate (BEM), thermal model integrated with an AFN, and a thermal model integrated with an AFN containing more representative wind pressure coefficient values obtained by a CFD simulation. Because this specific case study also provided heating and cooling utilizing mechanical systems, the relationship between natural ventilation and overheating hours would be challenging to prove. To efface this problem, the calibrated model was adjusted, and all mechanical systems removed, leaving natural ventilation as the only source of cooling for the building. After the model adjustment, by comparing the simulation results and the number of overheating hours predicted by each method, there will be an indication whether the assumptions commonly utilized in thermal model are suitable to adequately predict overheating risk or if more detailed model with integration of the AFN model is required when performing an overheating assessment. Figure 5 shows the average daily operative temperature (left) and air change rate (right) predicted with each modeling technique. Overall, the model with AFN and CFD values yielded the highest daily indoor operative temperatures and lowest air change per hour rates. This was already expected since all openings in apartment were located on the east façade, which is shielded by an adjacent building that reduces the potential of natural ventilation. Even without accounting for the neighboring buildings, the AFN model wielded closer results to the ones obtained with CFD (RMSE = 0.83°C) than the thermal model alone (RMSE = 1.77 °C), indicating that whenever possible, due to the easiness of combining this additional step with the thermal model, it is recommended to utilize at least the thermal model with AFN model when performing an overheating analysis. On the other hand, all models followed the same trend of indoor temperature, meaning that whenever the interest of the analysis is only to observe the overheating trends of the building, and not to calculate the exact number of overheating hours, the thermal model may provide an easy and fast tool to accurately perform the temperature analysis.
Figure 5. Room operative temperature (left) and room air changes per hour rate (right).

For the number of overheating hours analysis, the indoor temperature thresholds given by the European standard EN 16798-1 (table 2) was utilized for the assessment. The standard gives a temperature range where comfort is assumed to be met. Any hour that the indoor temperature exceeds the cooling threshold is considered an overheating hour if the room is occupied at that time.

Table 2. Temperature ranges defined by EN 16798-1 for building energy simulations.

| Type of building or space | Category | Temperature range for heating, °C | Temperature range for cooling, °C |
|--------------------------|----------|----------------------------------|----------------------------------|
|                          |          | Clothing ~ 1.0 clo               | Clothing ~ 0.5 clo               |
| Residential buildings    | I        | 21 – 25                          | 23.5 – 25.5                      |
| Sedentary activity ~ 1.2 met | II      | 20 – 25                          | 23 – 26                          |
|                          | III      | 18 – 25                          | 22 – 27                          |

Following the same trend observed in figure 5, the thermal model severely underestimated the number of overheating hours due to the overestimation of natural ventilation cooling potential. Both the AFN model and AFN model with CFD found fairly similar overheating hours results, which suggests that whenever the more complex CFD analysis of the building surroundings is unable to be executed, the easier AFN coupling is also a fairly accurate alternative. Nevertheless, the thermal model in conjunction with the assumed design values underestimated the number of overheating hours by 39.9%, which is a considerable difference when analyzing the summer performance of a passive house. Table 3 shows the number of overheating hours obtained with each modeling technique.

Table 3. Number of overheating hours.

| Overheating Hours (EN 16798-1 – Category II) |
|---------------------------------------------|
| BEM | AFN Model | AFN Model with CFD |
| 1045 | 1367       | 1656               |

5. Conclusion

The main investigation performed in this research focused on understanding the influence of airflow modeling method on the number of overheating hours. By utilizing different airflow modelling techniques, results showed a significant variation between the simplified airflow of the thermal model and the dynamically calculated multizone airflow provided by the airflow network model. There was an average 36.9% decrease in the overheating hours of the studied bedroom from the results utilizing the thermal model compared to the multizone airflow model. It can be concluded that the specification of air change rates from which the flow rates are calculated based on the volume of the room does not represent the realistic airflow in buildings. Both the orientation of the window openings in respect to the wind direction and the existence of wind-blocking elements around the studied building, which determines the pressure difference and hence the airflow rate, are neglected when utilizing the thermal model alone. The large difference in the number of overheating hours emphasizes the need for a more detailed analysis of the airflow in building simulations.
While this research thoroughly studied the effect of different simulation tools on the results of the overheating assessment of passive houses, there are still some aspects that need to be analyzed in detail to draw more robust conclusions on the topic of this paper. Further attention in future work is necessary to determine if this phenomenon is indeed accurate in free running passive houses that utilize natural ventilation as the main form of removing heat. Model uncertainty, primarily the uncertainty related to the AFN and CFD simulations also need to be taken into account for more reliable results. A sensitivity analysis measuring the sensibility of the output to both airflow network and CFD parameter uncertainty is necessary. Finally, to solidify conclusion regarding the importance of the CFD analysis when performing an assessment of overheating risk, more case studies within different urban typologies (urban, sub-urban and rural) is encouraged.

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