Overheating assessment in Passivhaus dwellings: the influence of prediction tools

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ABSTRACT

Thermal comfort during the summer in the Passivhaus concept relies mainly on natural ventilation to provide indoor cooling. Do airflow modeling tools accurately predict overheating in summer and for anticipated warmer climates? What effect do simplifications of airflow modeling techniques have on the overheating assessment of Passivhaus dwellings? Measured data and a calibrated thermal model are employed in the present study to address this question. The calibrated model is then used to create a standalone building energy model (BEM), a BEM coupled with an airflow network model (AFN), and a BEM coupled with an AFN supported by the wind pressure coefficients obtained from computational fluid dynamics (CFD) simulation. The outcome of each modeling approach was then compared against each other within three different European climates. Results showed that the overheating frequency prediction found with the default design infiltration and natural ventilation inputs commonly used in the literature agreed fairly with those obtained from the AFN + CFD in temperate or colder climates (< 2% difference), but were significantly underestimating overheating in Passivhaus buildings located at warmer climates (9.4% difference). For Passivhaus dwellings in warmer climates, the airflow modeling approach is unlikely to provide for an accurate estimation of the overheating incidence.

PRACTICE RELEVANCE

With overheating becoming a major issue in Europe, the prediction of the indoor thermal performance by using dynamic building simulations became common practice by researchers and practitioners. This study scrutinized the three most common methods of modeling airflow phenomena (BEM, AFN and CFD) when performing building energy simulations. For Passivhaus buildings located in warmer climates, the choice of airflow

modeling approach is important to obtain an accurate prediction of overheating. The study found that BEM is unlikely to be suitable for predicting the extent and frequency of overheating in home and warm climates. The AFN + CFD approach provides a more reliable approach for predicting overheating in hot and warm summer climates. For Passivhaus homes in locations with cooler summers, the difference between modeling approaches became mostly insignificant, so the simpler BEM models may be sufficient when performing an overheating analysis in that context.

1. INTRODUCTION

The building sector accounts for approximately 40% of the world's annual energy consumption (Balaras *et al.* 2005; EIA 2020). Of this, as much as 60–70% of the building energy consumption is for space heating and cooling (Wang 2015). With the goal of providing thermal comfort while reducing the energy demand for heating and cooling, the 'passive design' or 'passive house' concepts (*e.g.* optimal building orientation, cross-ventilation, improved insulation, airtight envelope and minimal use of mechanical cooling systems) have been widely adopted for high-performance buildings (Lechner 2014).

This paper investigates the Passivhaus standard, which can reduce the heating needs of buildings by a factor of 10 (Mueller & Berker 2013). The Passivhaus Institut (PHI) set the heating and cooling demand threshold at 15 kWh/m^2, and five key passive design principles were established: high thermal insulation, an airtight envelope, the elimination of thermal bridges, high-performance windows and ventilation heat recovery (Feist *et al.* 2007). The application of the Passivhaus standard to newly constructed dwellings is considered an important approach to achieve the Energy Performance of Buildings Directive (EPBD) goal of a 40% reduction in green gas emissions by 2030 (EPBD 2018).

In order to reduce the occurrence of overheating in summer (Figueiredo *et al.* 2016; Hidalgo *et al.* 2015; Sameni *et al.* 2015), higher thermal insulation, external shading and natural ventilation are common strategies that replace the need for conventional mechanical systems (Samuel *et al.* 2013). In response to the increasing demand for Passivhaus dwellings, research is needed to better understand the strengths, weaknesses and limitations of dynamic building simulations for overheating prediction. Understanding the capabilities and limitations of each modeling approach is essential to create models that are neither too simplistic nor complex.

A significant research gap exists for understanding the effect of different modeling methodologies on the number of overheating hours predicted by dynamic building simulations. As Passivhaus buildings rely on natural ventilation to provide free cooling during the hotter summer days, other modeling approaches need to be considered as options. For example, the airflow network (AFN) model and computational fluid dynamics (CFD) can more accurately represent airflow phenomena and may be useful tools.

This paper investigates and compares these different modelling techniques to ascertain the reliability of their overheating predictions. A comparative analysis of different airflow modeling approaches for predicting overheating in Passivhaus dwellings is used to identify the number of overheating hours predicted by the building energy model (BEM), BEM coupled with an AFN, and BEM coupled with an AFN and CFD.

The paper is structured as follows. Section 2 briefly reviews the existing Passivhaus research conducted in European countries (*e.g.* Portugal, UK, France, Denmark, Sweden, Spain and Italy) to ascertain past and current performance of the Passivhaus standard in relation to overheating. Section 3 describes the methods used: a calibrated thermal model as the basis to create a standalone BEM, BEM coupled with AFN, and BEM coupled with an AFN with the addition of wind pressure coefficients obtained from a CFD simulation. Section 4 presents the results in three different European climates with distinct representations of airflow. Sections 5 discusses

the implications of these findings and notes the variance in the outputs from different modeling approaches. Section 6 concludes by considering their reliability to predict outdoor temperatures during the summer.

2. LITERATURE REVIEW

The literature dealing with Passivhaus has primarily explored mainly technological and financial conditions, *e.g.* economic viability (Audenaert *et al.* 2008; Badescu 2007), energy performance (Mahdavi & Doppelbauer 2010; Schnieders & Hermelink 2006) and optimal operation (Feist *et al.* 2005). This research demonstrated the superior energy efficiency that Passivhaus had as compared with standard buildings. Very little attention was initially 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 Passivhaus, research interests shifted. Researchers and practitioners started to widely use dynamic building energy simulations to investigate indoor thermal comfort, and the availability of data obtained from the first batch of Passivhaus allowed for the comparison between simulated and measured values. More recently, with growing concern about climate change, experiments have begun investigating the future performance of Passivhaus (Dodoo *et al.* 2014; McLeod *et al.* 2013).

Overheating is now commonly observed even in countries with temperate climates (Lomas & Porritt 2017). This identified many European climates, where most of the monitored Passivhaus dwellings built after 2008 are now experiencing increasing occurrence of indoor overheating events. Monitoring studies between 2009 and 2015 have reported Passivhaus buildings are susceptible to overheating during the summer. Hidalgo *et al.* (2015) performed an overheating analysis using dynamic building simulation for a certified passive building in Spain and observed that the indoor air temperature surpassed 25°C threshold proposed by the Passive House Planning Package (PHPP) during 11.8% of the occupied period. Mlakar & Štrancar (2011) analyzed the performance of a passive building located in Slovenia and determined that without strategies such as external shading and night-purge ventilation the building would face indoor temperatures far above 26°C. Similarly, Ridley *et al.* (2013) monitored the performance of a Passivhaus in London between August 2011 and July 2012 and found that the operative temperature in the living room exceeded the thresholds proposed by the Chartered Institution of Building Services Engineers' (CIBSE) *Guide A* (2006) of 28°C for 123 h and that in the bedroom exceeded 26°C for 43 h during that period.

As a response to the problem, overheating evaluation during the summer through the PHPP became another criterion for certification. Even though the PHPP is a reliable and validated tool for the evaluation of a building's heating and cooling demand through the use of monthly balance calculations (Charron 2019), these results do not follow the same level of accuracy when predicting the indoor thermal performance. Fletcher *et al.* (2017) analyzed the overheating frequency calculated with the PHPP against measured values obtained with thermal sensors. They found that while the PHPP estimated only a 5% overheating frequency for the entire household, the sensors in the bedroom and lounge registered overheating frequencies of 51.2% and 20.8%, respectively. Similarly, Finegan *et al.* (2020) performed a comparative analysis of measured and simulated overheating frequency with the PHPP threshold of 25°C and found that because the PHPP simulation relies on a dwelling average temperature, it estimates an overheating frequency of 0%. However, the measurements indicate that overheating occurred on 69 days in the bedroom and for 10–11 days in other parts of the home.

The typical process for evaluating overheating risks for Passivhaus dwellings with dynamic building simulation entails creating a BEM, selecting an appropriate thermal comfort criterion, and comparing the results obtained from the simulation with the limits and thresholds dictated by the thermal comfort criterion. Although the choice of thermal comfort standard varies from study to study, many designers rely on the standalone BEM. In this standard, ventilation and infiltration rates are reflected as model inputs, even though natural ventilation plays a fundamental role in

the output of the assessment. For example, Figueiredo *et al.* (2016) used a constant total airflow rate of 0.6/h 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.

(p. 196)

McLeod *et al.* (2013) chose an infiltration rate of 0.035 air changes per hour (ACH) and an airflow rate of 30 m³/per person/h and concluded that:

> careful attention must be paid to the design assumptions and assessment criteria used to evaluate future overheating risks.

(p. 206)

In addition, the possibilities of purge ventilation through opening windows were identified as limited or non-existent in urban contexts. Hidalgo *et al.* (2015) used a total air change rate of 0.7/h during all the summer period to replicate natural ventilation when windows are open, while Němeček & Kalousek (2015) went further and created two ventilation profiles: 4–5/h for overnight ventilation and 0.1/h during the day. Natural ventilation is generally acknowledged as a fundamental system to provide cooling and avoid overheating during the summer, but the airflow modeling method is either not mentioned in the paper or is stated as an input value without justification.

The implementation of more complex airflow modeling approaches has been successfully demonstrated for naturally ventilated buildings (Djunaedy *et al.* 2003; Schulze & Eicker 2013). There is a significant difference between the assumed base infiltration values and that generated by the AFN. However, the current overheating assessment process for Passivhaus dwellings are still solely based on the BEM.

3. METHODS

The primary objective of this paper is to perform a comparative analysis between different airflow modeling approaches while predicting overheating in Passivhaus dwellings that rely on natural ventilation for cooling during the summer. Specifically, the aim is to identify the difference in the number of overheating hours predicted by the BEM, BEM coupled with an AFN, and BEM coupled with an AFN with the addition of wind pressure coefficients provided by a CFD simulation.

Consequently, the research methods were divided into three stages:

- Model inputs, where all the information regarding the case study and indoor measured data were obtained.

- Building energy simulation, where the model inputs are analyzed and included within each modeling approach to generate results.

- Overheating analysis, where the results of each simulation method are used to analyze overheating, its outcome is compared with each other, and the climate characteristics are analyzed.

The change in airflow modeling approach within the same case study allowed the evaluation of the advantages and shortcomings of each modeling approach for overheating analysis. This may serve as a guideline for the overheating assessment of other models built around similar context and climate.

The Fiorita Passive House was chosen because the Passivhaus building criteria do not change according to climate. A Passivhaus built in Italy will often have a very similar wall *R*-value, window *U*-value and solar heat gain coefficient (SHGC), and mechanical systems of certified buildings in Germany, Sweden or Portugal. This specific case study also provided cooling through mechanical systems, so the relationship between airflow modeling and overheating hours could be obscured by mechanical cooling. Thus, after calibrating the model according to occupancy schedule and

flat operation, all cooling mechanical systems were omitted leaving natural ventilation as the only source of cooling during the summer for the building during the overheating analysis comparison. After the model adjustment, comparison of the simulation results and the number of overheating hours predicted by each method according to the threshold incidence and temperature defined by the PHPP (*Table 1*) will provide an indication about whether the assumptions commonly used in thermal model are suitable to adequately predict overheating risk.

HOURS > 25°C	HOURS/YEAR	ASSESSMENT
> 15%	> 1314	Catastrophic
10–15%	**876–1314**	**Overheating**
5–10%	438–876	Acceptable
2–5%	175–438	Optimal
0–2%	0–175	Excellent

Table 1: Temperature ranges defined by the Passive House Planning Package (PHPP) for building energy simulations.

3.1 CASE STUDY BUILDING

This study used the energy model of the Fiorita Passive House, a multi-storey apartment building located within the Mediterranean climate of the city of Cesena, Italy. The monitored apartment is located on the top floor of the building and included the measurement of air temperature (°C), relative humidity (%), CO_2 concentration (ppm) and surface temperature (°C) from 22 April 2016 to 22 April 2017 at an hourly time-step through probes and sensors installed at the master bedroom of the apartment. The monitoring process is more thoroughly explained by Costanzo *et al.* (2018).

All Fiorita Passivhaus envelope assemblies were built to the PHI certification criteria. The exterior walls have a total corresponding *U*-value of 0.119 W/m²K, the roof assembly has a total resulting *U*-value of 0.095 W/m²K, and the triple-glazed windows with a center-of-glass *U*-value of 0.6 W/m²K. The airtightness of the building was tested according to EN ISO 9972 Standard (ISO, 2015) and the number of ACH for infiltration at 50 Pa was n50= 0.41/h. 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.

As a Passivhaus-certified building, all the thermophysical properties of the building façade are fully detailed and publicly available in the building certification granted by the PHI (Lang 2009), and summarized in *Table 2*.

U-VALUE (W/M²K)				DESIGN AIRTIGHTNESS AT 50 PA (ACH)		MECHANICAL SYSTEMS
BASEMENT FLOOR/FLOOR SLAB	EXTERIOR WALLS	ROOF	GLAZING	BEM MODEL	COUPLED MODEL	MVHR, VRF
0.185	0.119	0.095	0.6	0.41	Dynamic	Ventilation with efficient specific heat recovery of 91%

Table 2: Fiorita Passivhaus assemblies *U*-value and heating, ventilation and air-conditioning (HVAC) summary.

Note: ACH = air changes per hour; BEM = building energy model; MVHR = mechanical ventilation with heat recovery; VRF = variable refrigerant flow.

3.2 ENERGY MODEL AND CALIBRATION

The entire building was modeled using Rhino 3D version 6.34, and the analyzed flat simulated with EnergyPlus through the Grasshopper plugins Ladybug and Honeybee (LBT) version 1.1.0 (Roudsari *et al.* 2013). LBT establishes the possibility of using Rhino 3D as a single platform for both the design and simulation of buildings, providing the full range of building environmental and performance analysis in the parametric platform of Grasshopper. The tool facilitates processes such as creating

thermal zones and assigning programs, construction sets, schedules, and internal loads for each space. While the tool helps users create better models, it also has its limitations such as the inability to model radiant heating, ventilation and air-conditioning (HVAC), detailed domestic hot water systems, and renewable energy systems. Since all neighboring flats are assumed to have a similar indoor experience, for simplicity they were all added in the model as context geometry and the walls and floors from the simulated flat in contact with these apartments were added as adiabatic surfaces (*Figure 1*). The analyzed building consists of four thermal zones: living room, kitchen, master bedroom and bathroom.

Given that all the thermophysical properties (conductivity, specific heat, thermal and solar absorptance) of construction materials are specified in the Passivhaus certification, most of the thermal model uncertainty relates to the building operation. An MVHR system with maximum flow rate of 230 m³/h and thermal efficiency of 90% was added in conjunction with an VRF system to keep the indoor temperature within the range of 19–28°C. Occupant behaviors and flat operation schedules (occupancy, lighting and equipment loads, *etc.*) were based on the US Department of Energy's (DoE) commercial reference buildings (Field *et al.* 2010) and adapted to the values commonly found in other Passivhaus dwellings studies (Blight & Coley 2013; Tronchin *et al.* 2018). Typical meteorological year (TMYx) weather data for the municipality of Forli, with hourly weather data available through 2018, were used in all calibration simulations for a better representation of a recent TMYx scenario in Italy (Lawrie & Crawley 2020).
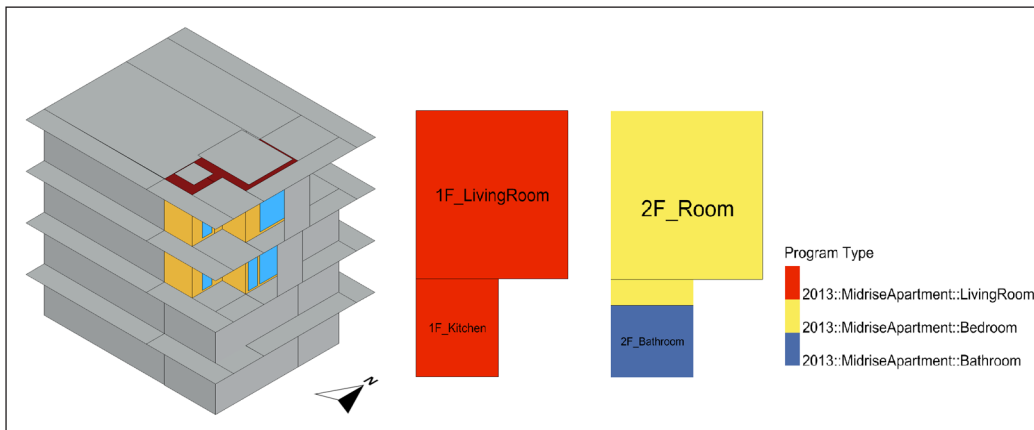

Figure 1: Model created using Rhinoceros 3D and Grasshopper using the Ladybug tools plugin.

The entire model, including all material parameters, occupant behavior and HVAC systems, were tested and calibrated by comparing the simulated hourly air temperature results with measured hourly data obtained with sensors located in the master bedroom. *Figure 2* shows the calibration results for the summer and shoulder seasons (23 April–14 October 2016), which demonstrates fairly accurate accordance with the measured temperatures.
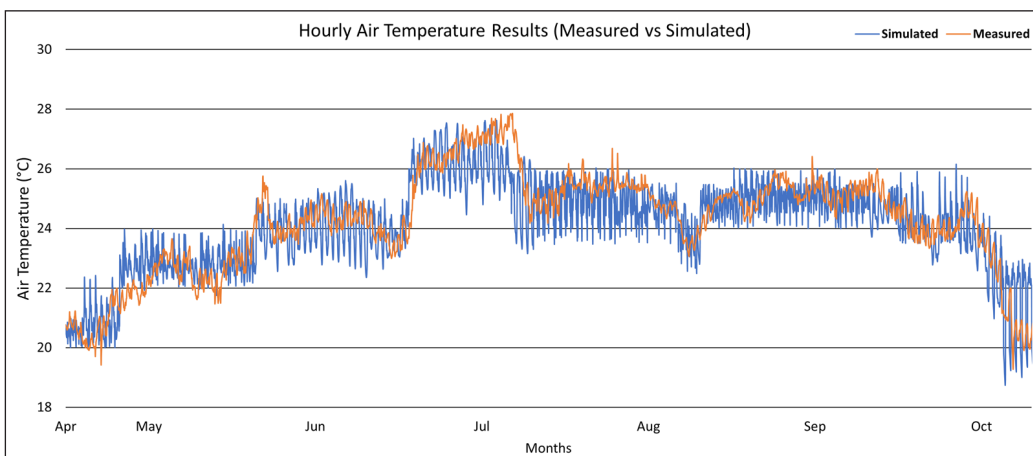

Figure 2: Comparison of simulated and measured air temperature results for the calibration process.

To further confirm the efficacy of the calibration process, both the daily difference between the maximum and minimum temperatures and the root mean squared error (RMSE) were performed for the entire duration of the simulation. *Figure 3* provides a visualization of the output difference between the measured and simulated data, where a maximum difference reported (grey area) is 1.89°C for the entire simulated period. The RMSE study showed an average error of 0.948°C, implying that the model is reliably representative of the case study.
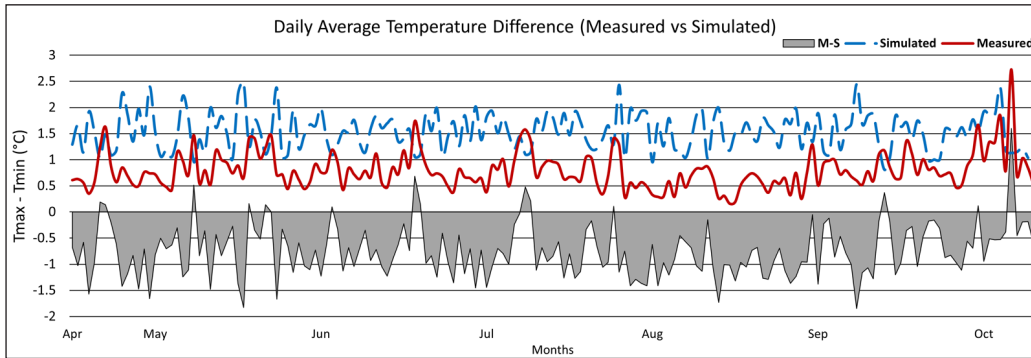
3.3 THERMAL MODEL, AIRFLOW NETWORK MODEL AND CFD ANALYSIS

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. In this scenario, it represents a free-running building where natural ventilation is the only source of cooling. By performing the analysis of thermal model in this way, the natural airflow modeling is emphasized and the results of the study become more applicable for other Passivhaus buildings with varying mechanical systems. As the thermal model is only based on heat balance principles, the inputs of design airflow rates are required. For infiltration, the value obtained from the blower door test of 0.41 ACH was used as default value, while 2.5 ACH was used for ventilation with a windows opening temperature set at 22°C, which is a value commonly used in building simulations (Consoli *et al.* 2017).

To simulate some form dynamic airflow rates in the thermal model, EnergyPlus relies on empirical models defined as functions of the temperature and the wind speed in relation to the design value inputted by the modeler:

$$\text{Infiltration} = (I_d)(F_s)\Big[A + B(\Delta T) + C(w) + D(w^2)\Big] \tag{1}$$

$$\text{Ventilation} = (V_d)(F_s)\Big[A + B(\Delta T) + C(w) + D(w^2)\Big] \tag{2}$$

where I_d and V_d are the design rates for infiltration and ventilation, respectively; F_s is the fraction of airflow rate in relation to the design value, which can also be used to simulate demand-controlled ventilation if connected to the fractional occupancy schedule of the room; A, B, C and D are the coefficient terms that weight temperature and wind speed influence on the airflow; ΔT is the temperature difference between the indoor and the outdoor; and w is wind speed.

In contrast to the thermal model, the AFN model can dynamically simulate airflow every time-step by calculating the total pressure difference between two air nodes. First, the pressure of each node is calculated according to equation (3), 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 (EnergyPlus 2021):

$$m_i = C_i \rho \frac{\Delta P_i}{\mu} \tag{3}$$

where m_i is the air mass flow rate; μ is air viscosity; ΔP_i is pressure difference; and C_i is the flow coefficient.

As the AFN model uses 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. However, its inclusion adds another layer of uncertainty to the model: occupant behaviors for window opening and closing as well as other input parameters, *e.g.* flow exponent, leakage area, discharge coefficient and wind pressure coefficients (C_p). Flow exponent and discharge coefficient are parameters that have a clear range of accepted values [0.5–0.75] (de Wit 2002). Additionally, 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 zone indoors and outdoors ($T_{in} > T_{out}$). For infiltration and wind pressure coefficients, both the Air Infiltration and Ventilation Centre (AIVC) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers' (ASHRAE) *Fundamentals Handbook 2001* provide effective leakage area (ELA) and façade wind pressure data for rectangular low-rise buildings with flat or pitched roofs and without any kind of wind-blocking elements (Orme & Leksmono 2002; Owen 2001). 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 building façade.

The AFN model can accurately calculate airflow according to a window's size, opening conditions, and location, wind availability and wind direction, due to the utilization of the default wind pressure coefficients. However, both the shape of the building and the presence of wind-blocking elements around the studied building are not taken into consideration in the base AFN model.

Directly coupling between BEM and CFD model was thoroughly studied (Zhai & Chen 2005). Nevertheless, the computational difficulties associated with the complex nature of CFD simulation can act as a deterrent. An alternative is to use CFD as an enhancement to the AFN model by supplying wind pressure coefficients more applicable to the geometry and surrounding context of the case study.

In this study, the area surrounding the Fiorita Passive House was modeled for a CFD analysis with Eddy3D version 0.3.8.0 (**Figure 4**), a Grasshopper plugin that servers as a user interface for the simulation engine BlueCFD based on the open-source CFD project OpenFOAM (Jasak 2009). The computational domain was created based on the recommendations labeled by Franke *et al.* (2007) and according to the findings of Costanzo *et al.* (2019), setting the domain dimensions to 300 × 245 × 70 m³ and a mesh size with 1,588,322 elements. The inlet local wind speed in all CFD analysis of this study were estimated according to equation (4) by applying terrain roughness and height corrections to the yearly average wind speed data obtained from the TMYx weather data for the municipality of Forli (Lawrie & Crawley 2020). While BlueCFD offers a variety of turbulence models, the re-normalization group (RNG) *k*-ε turbulence model proposed by Yakhot & Smith (1992) was used in this study due to its accuracy and computational efficiency. This can be represented as:

$$U_H = U_{met} \left(\frac{\delta_{met}}{H_{met}} \right)^{\alpha_{met}} \left(\frac{H}{\delta} \right)^{\alpha} \tag{4}$$

where U_H and U_{met} are the corrected and weather data wind speeds; δ and δ_{met} are the wind boundary layer thickness for the building local context and meteorological station; and α and α_{met} are the exponent for the local building terrain and meteorological station.

To account for the pressure caused by different wind directions, wind angles were simulated in a 45° interval (from 0 to 180°) and were used to calculate the pressure coefficient on each external façade. The C_p values obtained from the simulation were averaged for each façade area and then connected to their corresponding external air node as an input on the AFN model in EnergyPlus. These simulated C_p values (in contrast to those assumed on the baseline AFN) do account for the building's geometry, façade orientation and presence of wind-blocking elements around the analysed building when calculating airflow.
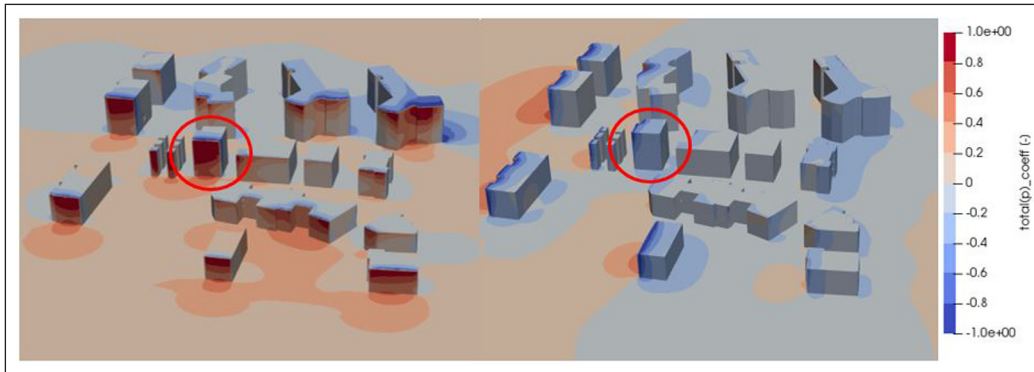
4. OVERHEATING RESULTS AND THE EFFECT OF DIFFERENT CLIMATES

This section examines the choice between all three modeling techniques: (1) a standalone thermal model with the specification of airflow rate (BEM), (2) a thermal model integrated with an AFN, and (3) a thermal model integrated with an AFN containing more representative wind pressure coefficients obtained by a CFD simulation. The three approaches were compared in terms of simulation outputs, overheating hours and overheating incidence according to the PHPP overheating criteria. All dynamic energy model runs were performed on three different climates using TMYx weather files for Forli in Italy, London in the UK and Helsinki in Finland (Lawrie & Crawley 2020).

4.1 MEDITERRANEAN CLIMATE SIMULATION RESULTS

The Mediterranean climate of Italy has very hot, dry summers and, for this study, will serve as a representation for the warmer climates within Europe. *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 ACH rates. This was already expected since all openings in the studied 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 yielded closer results to those obtained with CFD (RMSE = 0.83°C) than the standalone thermal model (RMSE = 1.77°C). This suggests that whenever possible, it is recommended that the thermal model is used with AFN when performing an overheating analysis in warmer climates. If the only interest is to observe the indoor thermal performance or overheating trends of the building, and not to assess the number of overheating hours, then the thermal model alone may provide an easy and fast tool to perform the simple temperature analysis.
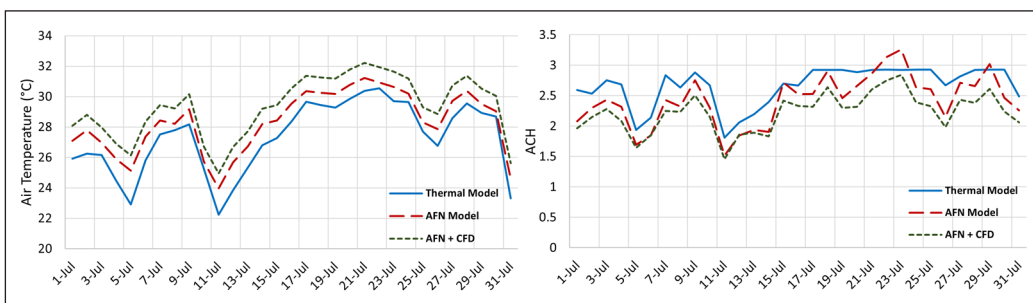
The thermal model severely underestimated the number of overheating hours due to the overestimation of natural ventilation cooling potential. Both the AFN model and AFN model with CFD found fairly similar overheating hours results. This suggests that whenever the more

complex CFD analysis of the building surroundings cannot be used, the AFN (coupled with BEM) is a relatively accurate alternative. Nevertheless, the thermal model in conjunction with the assumed design values underestimated the number of overheating hours by 39%. This yields a significant difference when analyzing the total incidence of overheating throughout the year. Although all three airflow modeling methods identify 'overheating' results as defined by the PHPP criteria, a significant difference can be found in the results. *Table 3* shows the number of overheating hours and incidence of overheating obtained with each modeling technique.

OVERHEATING ASSESSMENT (PHPP—25°C)		
	NUMBER OF OVERHEATING HOURS	**INCIDENCE OF OVERHEATING (%)**
BEM	1293	14.8%
AFN model	1834	20.9%
AFN model with CFD	2119	24.2%

Table 3: Number of overheating hours for the Passivhaus in Italy.

Note: AFN = airflow network model; BEM = building energy model; CFD = computational fluid dynamics; and PHPP = Passive House Planning Package.

4.2 TEMPERATE CLIMATE SIMULATION RESULTS

The simulation for the temperate climate of the UK, which has mildly warm and wet summers, reveals a similar pattern to the Mediterranean climate simulation results (*Figure 6*). The standalone thermal model continued to yield the lowest indoor temperatures while continuously having higher ACH in the bedroom. This suggests that even in climates with historically lower summer outdoor temperatures, using more accurate methods of modeling airflow has a measurable impact on the outcome of dynamic simulations.
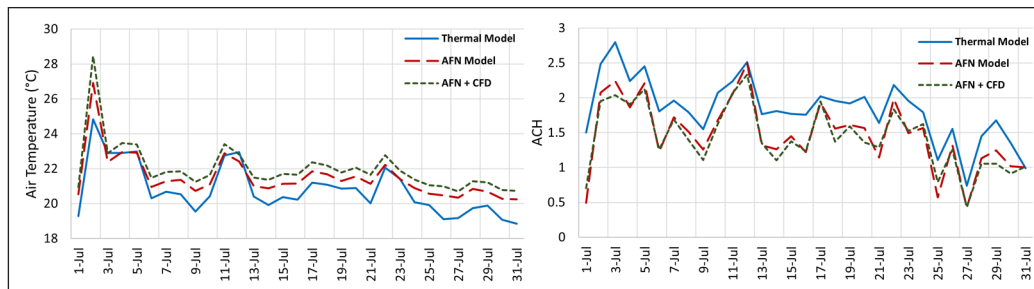

Figure 6: Master bedroom air temperature (left) and air changes per hour (right) in the UK.

As there is a significant difference in the number of overheating hours obtained between the CFD and BEM models (35.6% underestimation), both the temperature gap and incidence of overheating obtained by using the thermal model (RMSE = 1.39°C and 3.6% overheating) and AFN model (RMSE = 0.56°C and 4.8% overheating) was lower compared with the more complex CFD model (*Table 4*). This can be explained by two factors: (1) the lower outdoor temperatures mean overheating becomes less of an issue and natural ventilation plays a minor role on providing cooling to the building; and (2) the lower temperature of the wind allows for a higher effective reduction of the overall number of overheating hours.

OVERHEATING ASSESSMENT (PHPP—25°C)		
	NUMBER OF OVERHEATING HOURS	**INCIDENCE OF OVERHEATING (%)**
BEM	318	3.6%
AFN model	425	4.8%
AFN model with CFD	494	5.6%

Table 4: Number of overheating hours for the Passivhaus in the UK.

Note: AFN = airflow network model; BEM = building energy model; CFD = computational fluid dynamics; and PHPP = Passive House Planning Package.

4.3 BOREAL CLIMATE SIMULATION RESULTS

The last climate to be tested is the cooler climate encountered around the Scandinavian region, characterized by its short, mild and rainy summers. This third study makes clear that while there still is a difference in the results obtained by the three airflow modeling approaches, these are relatively minor compared with the results obtained at warmer climates (**Figure 7**). In this case, compared with the CFD results, the AFN model performed similarly to the temperate climate of London (RMSE = 0.56°C), but there was still an improvement in the thermal model results (RMSE = 0.80°C). This demonstrates that when the outdoor temperature is lower, the thermal model performs closer to the AFN plus CFD.
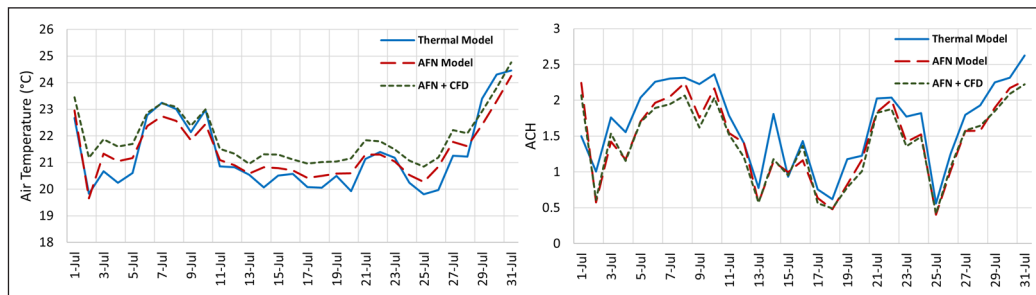

Figure 7: Master bedroom air temperature (left) and air changes per hour (right) in Finland.

The difference in the number of overheating hours and incidence also sustained a substantial reduction, with the difference between the BEM and CFD models decreasing to 22.7% (**Table 5**), while the difference in overheating incidence was negligible. In this type of climate, all three modeling approaches would correctly categorize the building as a 'not overheating' Passivhaus, the simpler BEM can be used instead of more complex airflow modeling approaches without compromising the overheating assessment result.

OVERHEATING ASSESSMENT (PHPP—25°C)

	NUMBER OF OVERHEATING HOURS	INCIDENCE OF OVERHEATING (%)
BEM	51	0.58%
AFN model	60	0.66%
AFN model with CFD	66	0.75%

Table 5: Number of overheating hours for the Passivhaus in Finland.

Note: AFN = airflow network model; BEM = building energy model; CFD = computational fluid dynamics; and PHPP = Passive House Planning Package.

5. DISCUSSION

Dynamic building simulations are established as the tool for overheating analysis. The authors analysed various types of dynamic energy modeling to better understand how different modeling approaches can affect the number of overheating hours of a building. The simulation demonstrated that as the building becomes more reliant on natural ventilation, the choice of modeling airflow technique becomes more important. When simulated using Italy's weather file with default design infiltration and ventilation values, the number of overheating hours predicted for the Fiorita Passive House was severely underestimated due to the overestimation of natural ventilation cooling potential. This was indicated by the higher number of ACH and lower indoor temperature. In the BEM, the window opening size and orientation in respect to the wind direction, and the existence of wind-blocking elements around the studied building are not considered. While it is true that in BEM airflow is simplified to a single user input, model uncertainty is also reduced due to the lower number of necessary inputs. To accurately simulate infiltration and ventilation in the AFN, it is necessary to include precise information on building envelope airtightness conditions (wall cracks, leakage areas, *etc.*), discharge coefficient, flow exponent values, and, of course, the wind pressure coefficients. These conditions can be more precisely calculated with CFD. Nevertheless,

the variance of results by using BEM as the sole airflow modeling tool decreased as the climate gets colder. For buildings in cooler climates (*e.g.* Scandinavia) that do not rely as much on natural ventilation or mechanical cooling systems, the simplistic BEM can still provide results in line with what is found using either AFN or AFN plus CFD. However, for buildings in warmer climates that rely on natural ventilation, the large variation in the output emphasizes the need for a more detailed analysis of the airflow in building simulations. In this context, the BEM method may not accurately assess the overheating risks.

6. CONCLUSIONS

Practitioners need to predict with confidence whether and to what extent a building design will overheat in summer. This is particularly vital for assessing the thermal performance of a Passive House design in summer—for both present and future climatic conditions. According to the conducted literature review, the effect of different airflow modeling approaches on the overheating assessment results of Passivhaus was identified as not yet fully addressed by current literature.

This investigation developed a more detailed understanding the influence of airflow modeling method on the number of predicted overheating hours. The results for warmer climates revealed a significant variation between different modelling techniques: the simplified airflow of the thermal model and the dynamically calculated multizone airflow provided by the airflow network model coupled with computational fluid dynamics (CFD) studies. The simplified thermal model reported fewer overheating hours (39%) and overheating frequency (9.4%) compared with the multizone airflow model coupled with CFD. Thus, the specification of air change rates based on the volume of the room does not represent the realistic airflow in buildings. A simplified thermal model with generic values is not able to accurately predict the extent of summer overheating in warm climates. For buildings that rely on natural ventilation for its thermal comfort, the use of simplified building energy model (BEM) model can lead to inaccurate assessment of the overheating risk for the building due to a lack of consideration of the actual geometry or surroundings which influence air flow.

Although this research studied the effect of different simulation tools on the results of the overheating assessment in Passivhaus buildings, some aspects warrant further study. First, this study is limited to the overheating assessment criteria proposed by the Passive House Planning Package (PHPP) for Passivhaus certification. There is a clear European focus in this study and more work needs to be done on a wider global range of climate settings. Further work needs to determine if this phenomenon is accurate for free running Passivhaus buildings that use natural ventilation as the main form of removing heat. Model uncertainty, primarily the uncertainty related to the airflow network model (AFN) and CFD simulations also need to be considered for more reliable results. Finally, to solidify conclusions regarding the importance of the CFD analysis when performing an assessment of overheating risk, more case studies are necessary to understand the role of the CFD simulations when modeling airflow within different urban, suburban and rural contexts.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA AVAILABILITY

Measured data obtained from the Fiorita Passive House have not been made openly available due to lack of consent from the involved bodies and due to data protection regulations.

REFERENCES

Audenaert, A., De Cleyn, S., & **Vankerckhove, B.** (2008). Economic analysis of passive houses and low-energy houses compared with standard houses. *Energy Policy*, 36(1), 47–55. DOI: *https://doi.org/10.1016/j.enpol.2007.09.022*

Badescu, V. (2007). Economic aspects of using ground thermal energy for passive house heating. *Renewable energy*, 32(6), 895–903. DOI: *https://doi.org/10.1016/j.renene.2006.04.006*

Balaras, C. A., Droutsa, K., Dascalaki, E., & **Kontoyiannidis, S.** (2005). Heating energy consumption and resulting environmental impact of European apartment buildings. *Energy and Buildings*, 37(5), 429–442. DOI: *https://doi.org/10.1016/j.enbuild.2004.08.003*

Blight, T. S., & **Coley, D. A.** (2013). Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings. *Energy and Buildings*, 66, 183–192. DOI: *https://doi.org/10.1016/j.enbuild.2013.06.030*

Charron, R. (2019). *PHPP V9.6 Validation using ANSI/ASHRAE Standard 140-2017*. *https://www.passivehousecanada.com/wp-content/uploads/2019/02/PHPP-ASHRAE-140-Validation-Report-Jan-23-2019.pdf*

CIBSE. (2006). *CIBSE Guide A*. Chartered Institution of Building Services Engineers (CIBSE). *https://www.cibse.org/knowledge/knowledge-items/detail?id=a0q20000008I79JAAS*

Consoli, A., Costanzo, V., Evola, G., & **Marletta, L.** (2017). Refurbishing an existing apartment block in Mediterranean climate: Towards the Passivhaus standard. *Energy Procedia*, 111, 397–406. DOI: *https://doi.org/10.1016/j.egypro.2017.03.201*

Costanzo, V., Fabbri, K., & **Piraccini, S.** (2018). Stressing the passive behavior of a Passivhaus: An evidence-based scenario analysis for a Mediterranean case study. *Building and Environment*, 142, 265–277. DOI: *https://doi.org/10.1016/j.buildenv.2018.06.035*

Costanzo, V., Yao, R., Xu, T., Xiong, J., Zhang, Q., & **Li, B.** (2019). Natural ventilation potential for residential buildings in a densely built-up and highly polluted environment. A case study. *Renewable Energy*, 138, 340–353. DOI: *https://doi.org/10.1016/j.renene.2019.01.111*

de Wit, M. S. (2002). Uncertainty in predictions of thermal comfort in buildings. PhD thesis, Delft University of Technology. *http://resolver.tudelft.nl/uuid:a231bca8-ec81-4e22-8b34-4bafc062950e*

Djunaedy, E., Hensen, J., & **Loomans, M.** (2003). Toward external coupling of building energy and airflow modeling programs. *ASHRAE Transactions*, 109(2), 771–787.

Dodoo, A., Gustavsson, L., & **Bonakdar, F.** (2014). Effects of future climate change scenarios on overheating risk and primary energy use for Swedish residential buildings. *Energy Procedia*, 61, 1179–1182. DOI: *https://doi.org/10.1016/j.egypro.2014.11.1048*

EIA. (2020). *Annual energy outlook 2020*. Energy Information Administration (EIA).

EnergyPlus. (2021). *9.6.0: The encyclopedic reference to EnergyPlus input 601 and output*. US Department of Energy. *https://energyplus.net/assets/nrel_custom/pdfs/pdfs_v9.6.0/InputOutputReference.pdf*

EPBD. (2018). Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency. *Official Journal of the European Union*, 156(75). *https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2018.156.01.0075.01.ENG*

Feist, W., Pfluger, R., Kaufmann, B., Schnieders, J., & Kah, O. (2007). *Passive house planning package 2007* (Specifications for Quality Approved Passive Houses, Technical Information PHI-2007/1 (E)). Passivhaus Institut (PHI). *http://www.eerg.it/passive-on.org/CD/4.%20PHPP%202007%20Demo/Contents_Manual.pdf*

Feist, W., Schnieders, J., Dorer, V., & Haas, A. (2005). Re-inventing air heating: Convenient and comfortable within the frame of the Passive House concept. *Energy and Buildings*, 37(11), 1186–1203. DOI: *https://doi.org/10.1016/j.enbuild.2005.06.020*

Field, K., Deru, M., & Studer, D. (2010). *Using DoE commercial reference for simulation studies*. SimBuild. *https://www.nrel.gov/docs/fy10osti/48588.pdf*

Figueiredo, A., Kämpf, J., & Vicente, R. (2016). Passive house optimization for Portugal: Overheating evaluation and energy performance. *Energy and Buildings*, 118, 181–196. DOI: *https://doi.org/10.1016/j.enbuild.2016.02.034*

Finegan, E., Kelly, G., & O'Sullivan, G. (2020). Comparative analysis of Passivhaus simulated and measured overheating frequency in a typical dwelling in Ireland. *Building Research & Information*, 48(6), 681–699. DOI: *https://doi.org/10.1080/09613218.2019.1691490*

Fletcher, M., Johnston, D., Glew, D., & Parker, J. (2017). An empirical evaluation of temporal overheating in an assisted living Passivhaus dwelling in the UK. *Building and Environment*, 121, 106–118. DOI: *https://doi.org/10.1016/j.buildenv.2017.05.024*

Franke, J., Hellsten, A., Schlünzen, K. H., & Carissimo, B. (2007). Best practice guideline for the CFD simulation of flows in the urban environment—A summary. In *11th Conference on Harmonisation within Atmospheric Dispersion Modelling for Regulatory Purposes*, Cambridge, UK. Cambridge Environmental Research Consultants. *https://research.aalto.fi/en/publications/best-practice-guideline-for-the-cfd-simulation-of-flows-in-the-ur*

Hidalgo, J. M., Psomas, T., García-Gáfaro, C., Heiselberg, P., & Millán, J. A. (2015). Overheating assessment of a passive house case study in Spain. *Paper presented at the 36th AIVC Conference*, Madrid. Spain.

ISO. (2015). *EN ISO 9972: Thermal performance of buildings—Determination of air permeability of buildings—Fan pressurization method*. International Standard Organization (ISO). *https://www.iso.org/standard/55718.html*

Jasak, H. (2009). OpenFOAM: Open source CFD in research and industry. *International Journal of Naval Architecture and Ocean Engineering*, 1(2), 89–94. DOI: *https://doi.org/10.2478/IJNAOE-2013-0011*

Lang, G. (2009). *International Passivhaus database. Establishment of a co-operation. https://passivehouse-database.org/index.php?lang=en*

Lawrie, L. K., & Crawley, D. B. (2020). *Development of global typical meteorological years (TMYx) (2019)*. *https://climate.onebuilding.org/*

Lechner, N. (2014). *Heating, cooling, lighting: Sustainable design methods for architects*. Wiley. DOI: *https://doi.org/10.1080/09613218.2017.1256136*

Lomas, K. J., & Porritt, S. M. (2017). Overheating in buildings: Lessons from research. *Building Research & Information*, 45 (1–2), 1–18. DOI: *https://doi.org/10.1080/09613218.2017.1256136*

Mahdavi, A., & Doppelbauer, E.-M. (2010). A performance comparison of passive and low-energy buildings. *Energy and Buildings*, 42(8), 1314–1319. DOI: *https://doi.org/10.1016/j.enbuild.2010.02.025*

McLeod, R. S., Hopfe, C. J., & Kwan, A. (2013). An investigation into future performance and overheating risks in Passivhaus dwellings. *Building and Environment*, 70, 189–209. DOI: *https://doi.org/10.1016/j.buildenv.2013.08.024*

Mlakar, J., & Štrancar, J. (2011). Overheating in residential passive house: Solution strategies revealed and confirmed through data analysis and simulations. *Energy and Buildings*, 43(6), 1443–1451. DOI: *https://doi.org/10.1016/j.enbuild.2011.02.008*

Mueller, L., & Berker, T. (2013). Passive House at the crossroads: The past and the present of a voluntary standard that managed to bridge the energy efficiency gap. *Energy Policy*, 60, 586–593. DOI: *https://doi.org/10.1016/j.enpol.2013.05.057*

Němeček, M., & Kalousek, M. (2015). Influence of thermal storage mass on summer thermal stability in a passive wooden house in the Czech Republic. *Energy and Buildings*, 107, 68–75. DOI: *https://doi.org/10.1016/j.enbuild.2015.07.068*

Orme, M., & Leksmono, N. (2002). *AIVC Guide 5: Ventilation modelling data guide* (AIC-GUI, 5). International Energy Agency, Air Infiltration Ventilation Center. *https://www.aivc.org/sites/default/files/members_area/medias/pdf/Guides/Ventilation%20Modelling%20Data%20Guide_web.pdf*

Owen, M. (2001). *ASHRAE fundamental handbook*. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). *https://www.ashrae.org/technical-resources/ashrae-handbook*

Ridley, I., Clarke, A., Bere, J., Altamirano, H., Lewis, S., Durdev, M., & Farr, A. (2013). The monitored performance of the first new London dwelling certified to the Passive House standard. *Energy and Buildings*, 63, 67–78. DOI: *https://doi.org/10.1016/j.enbuild.2013.03.052*

Roudsari, M. S., Pak, M., & Smith, A. (2013). Ladybug: a parametric environmental plugin for grasshopper to help designers create an environmentally-conscious design. In *Proceedings of the 13th International IBPSA conference*, August, Lyon, France.

Sameni, S. M. T., Gaterell, M., Montazami, A., & Ahmed, A. (2015). Overheating investigation in UK social housing flats built to the Passivhaus standard. *Building and Environment*, 92, 222–235. DOI: *https://doi. org/10.1016/j.buildenv.2015.03.030*

Samuel, D. L., Nagendra, S. S., & Maiya, M. (2013). Passive alternatives to mechanical air conditioning of building: A review. *Building and Environment*, 66, 54–64. DOI: *https://doi.org/10.1016/j. buildenv.2013.04.016*

Schnieders, J., & Hermelink, A. (2006). CEPHEUS results: Measurements and occupants' satisfaction provide evidence for Passive Houses being an option for sustainable building. *Energy Policy*, 34(2), 151–171. DOI: *https://doi.org/10.1016/j.enpol.2004.08.049*

Schulze, T., & Eicker, U. (2013). Controlled natural ventilation for energy efficient buildings. *Energy and Buildings*, 56, 221–232. DOI: *https://doi.org/10.1016/j.enbuild.2012.07.044*

Tronchin, L., Manfren, M., & James, P. A. (2018). Linking design and operation performance analysis through model calibration: Parametric assessment on a Passive House building. *Energy*, 165, 26–40. DOI: *https:// doi.org/10.1016/j.energy.2018.09.037*

Wang, Y. (2015). *Optimization for building control systems of a school building in Passive House Standard*. Technische Universität München. *https://mediatum.ub.tum.de/?id=1253332*

Yakhot, V., & Smith, L. M. (1992). The renormalization group, the ε-expansion and derivation of turbulence models. *Journal of Scientific Computing*, 7(1), 35–61. DOI: *https://doi.org/10.1007/BF01060210*

Zhai, Z. J., & Chen, Q. Y. (2005). Performance of coupled building energy and CFD simulations. *Energy and Buildings*, 37(4), 333–344. DOI: *https://doi.org/10.1016/j.enbuild.2004.07.001*