INDOOR AIR QUALITY AND COMFORT IN NATIVE AMERICAN SHELTERS: SIMULATION AND ACTUAL DATA ANALYSIS

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ABSTRACT

The wigwam was a Native American shelter built in the north-eastern United States. This study determined if these structures supply comfort to human beings using modern measurement standards and if they provide indoor air quality levels that are healthy. Keene State College faculty and students built a full-size example of a wigwam and monitored data indoors and outdoors. When a fire was introduced into the wigwam to produce comfortable indoor temperatures, the analysis of air temperature and relative humidity, along with CO_2, VOC, and $PM_{2.5}$ levels, determined indoor air quality and comfort. By having a full-size example of a wigwam, the authors were able to compare the accuracy of a digital energy model. Comfort can be accomplished even when using modern standards in this native structure. Temperature, humidity, and rainfall exposure can all be controlled to acceptable levels. Indoor air quality is always at good levels when a fire is not involved because the indoor air in the wigwam is the same as exterior quality levels. However, the particulates and VOC introduced into the environment are at dangerous levels with an open fire. A wood stove with a flue pipe to the exterior was used to reduce the pollutants to acceptable and safe levels.

Keywords: Native American shelters, indoor air quality.

1 INTRODUCTION

A sufficient correlation exists between the health complications experienced by the Native American population and the unhealthy level of exposure to damaging particles from birth to death. Much of the harmful particulate matter in these communities originated from burning biomass freely in a compact living area with only a small opening to release the generated smoke. Wood-burning fireplaces and stoves have been familiar heating sources among residences around the globe for centuries. Aside from aesthetic preferences, many people prefer these methods due to their lower cost and lower carbon dioxide output than other heating sources which burn fossil fuels. Another factor to consider is the technology being used to burn wood.

The validation of energy use through software programs has proven to be a growing interest, especially in the past few years, with studies published across various software. Current building energy simulation tools provide the option of considering natural ventilation as a solution for saving energy and the capability to examine heating and cooling loads, ventilation, infiltration, and the generation of CO_2. To assess the simulation tools, customary metrics used to compare actual and simulated results include root mean square error (RSME), normalized mean boas error (NMBE), coefficient of variation of normalized root mean square error (CVRMSE), and coefficient of determination (R^2).

This article offered a proper procedure to simulate the heat source of sensible heat that did not change the humidity ratio, as it was based on the data measured from the prototype. At the same time, the calibration process can be used to assess the thermal behaviour of any given building. This study seeks to extend the knowledge and understanding required for successfully integrating building performance simulation (BPS) tools at the early stages of the building design process and code compliance. EnergyPlus and IES, were compared and

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discussed using a prototype of a Native American shelter typology. Only a rudimentary heating system and natural ventilation were the strategies to achieve an acceptable comfort level. The main goal of this research was to recognize the innovative value of the historic wigwam holding the opportunity to function as a temporary habitable dwelling in line with Westernized standards of comfort. While also taking this opportunity of studying comfort in a wigwam to compare with digital software to validate the software's ability to accurately predict how a simple dwelling responds to the environment and heating input.

2 LITERATURE REVIEW

Historically, constructing a wigwam could take one to three weeks due to the size and the number of people working on it [1], [2]. A uniform curved shape of the wigwam and wetu allowed the interior space to be evenly cooled or heated efficiently while withstanding precipitation effects. These shelters would be built on hunting and fishing grounds and acted as a lodge during specific seasonal farming months [3]. When these months passed, native people would leave the structural pieces of the wigwam and take the coverings of the shelter with them [4]. Upon returning, they would reassemble the coverings on the already existing frame [5].

Building energy simulation tools enable users to compute how much energy a building consumes, its hourly variation of relative humidity and temperature, and the thermal simulation of naturally ventilated buildings [6].

Parametric analysis screens also provide insight into the effect of design parameter variations on performance criteria [7], [8]. Furthermore, the EnergyPlus engine has been used in previous articles to evaluate the energy performance of Native American shelters [9]. In addition to this, Design-Builder's simulation process has been validated using the Building Energy Simulation Test (BESTest), which the American Department of Energy recognizes to evaluate building energy simulation across program features [10], [11]. Scientific articles incorporated in the literature review were written by other authors who have investigated the criteria to clarify errors that commonly occur in these models and standardize the calibration process of modelling a building [12], [13].

Burning wood is close to carbon neutral since the only carbon dioxide that is being released into the atmosphere is that which was taken in and stored in the tree [14]. At the same time, air emissions are more variable when burning wood than many other types of fuel since the composition of its smoke depends on factors such as the wood species, the water content, and the combustion temperature [15]. Furthermore, the byproducts of woodsmoke, especially fine particulate matter, can affect individuals with pre-existing conditions, children, the elderly, and anyone who spends too much time close to the source of these emissions. Fireplaces and older woodstoves are less efficient and produce more emissions as well as have a more significant organic component in their smoke, and therefore likely have a greater impact on human lungs, whereas, with more efficient appliances such as pellet stoves and advanced wood stoves, inorganic components are found more often and find difficultly depositing into our respiratory system due to the fast coagulation of the particles, which allows it to expel quickly [16]. Fine particulate matter, hydrocarbons, carbon monoxide, and aldehydes are the most important woodsmoke byproducts to avoid when considering human health as they can reduce the air quality significantly, causing many negative health outcomes, the most common of those being cardiovascular and respiratory damage [17], [18].

3 MATERIALS AND METHODS

This section presents the methods to assess the wigwam prototype's ability to meet adequate standards of comfort and indoor air quality (IAQ). Moreover, data from the local environment, both inside and out of the wigwam was collected from October to December 2022. Information from a week in October and December was used as samples to be evaluated against ASHRAE defined standards of comfort and IAQ.

3.1 Site description and construction of the wigwam.

The building of a full-scale traditional wigwam started in July 2022 in Winchendon, Massachusetts (42.6871° N, 72.0440° W).

3.1.1 Site description

The prototype is placed in a neighbourhood of single-family wood-framed homes built in the late 19th or early 20th century. The typical is a two- or two and a half-storey building between 25 and 32 feet tall. The distance between homes varies; in some cases 70 to 80 feet apart, and in others 100 feet or more between houses, with a lawn utilizing that space. Some homeowners have trees and shrubs in the yard, whereas others have only a lawn. The closet home to 85 Lincoln Ave is to the north side and is 44 feet away. There is also a line of trees at the property line between the two homes, which is approximately cantered between the buildings. Closer to the wigwam, between the house and garage, there is a small maple tree north of the wigwam, which could influence breezes. Fig. 1 shows the position of the wigwam and the surrounding buildings.

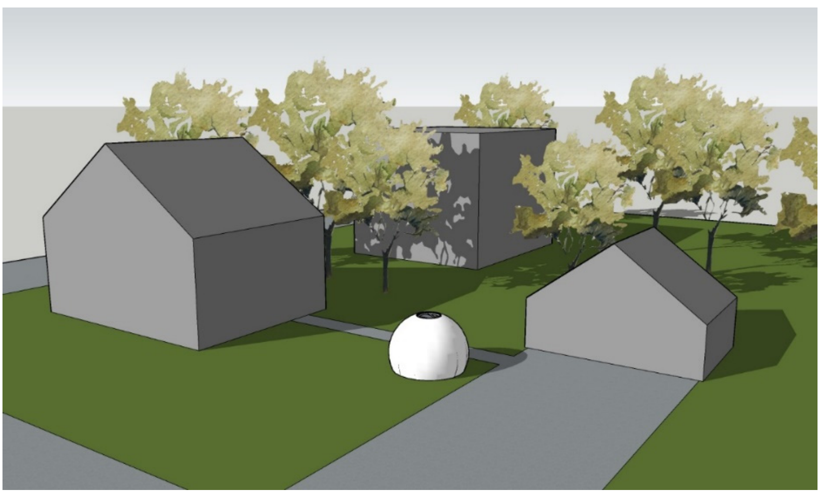

Figure 1: 3D model of the wigwam and the surrounding buildings.

3.1.2 Construction of the wigwam

A typical circular wigwam was about 6–10 feet tall and 10–14 feet in diameter [19], [20]. To traditionally assemble this shelter, first a relatively level and stable site would be selected, one that was not too soft or contained any sort of bedrock. Next, to construct the mainframe of the wigwam, young, flexible, and straight saplings no thicker than two inches in diameter would be gathered by the community (preferably swamp maple, red maple, or willow springs) [21]. These pieces would then be cut to 10–16 feet long, and have any imperfections, such as twigs, removed. By using a string tied to a fixed point and attaching a small stick (often replaced by feet) to the other end, an even circular outline could be traced in the ground to mark where the sapling poles could go [22]. Twelve to 16 holes would be plotted around this circumference and assigned to the saplings, with tobacco being added first to repel ground insects as well as for ritual purposes. After being bent into arches, bark fibres would be used to tie together any intersecting saplings [23]. Equally spaced sapling 'bands' or 'hoops' used for tensile strength in the wigwam would then be layered to encircle the mainframe [24]. For the entrance, two lower bands on the east side frame would remain unconnected. Finally, coverings typically made from overlapping birchbark pieces, or woven rush in the summer, were used to guarantee a watertight seal over the frame. A hole at the top would be left exposed to allow smoke from a fire to escape [25].

3.2 The 3D model

When replicating the wigwam using digital software, it is essential to start with both the base's radius and the wigwam's height. The circular base is created by using model lines with the desired radius. The next step was to mark where all the holes for the supports would be located along the circumference of the model's base. The actual supports of the wigwam are created by using void forms. The void form is used with corresponding holes that connect along the circumference of the base. When the void form interacts with the mass previously created, it leaves a curved line that represents the saplings used to develop the actual wigwam. Fig. 2 illustrates a diagram of the wigwam elements, from the circle layout to the structural elements and the envelope.

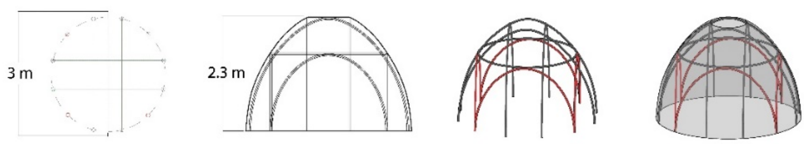

Figure 2: Diagram of the construction phases.

3.3 Simulation software

Since 1996, the US Department of Energy has maintained a directory of approximately one hundred computational tools [26], [27]. EnergyPlus was mainly conceived as a simulation engine without a user interface, combining and expanding the characteristics of BLAST and DOE–2 [28]. DOE provides significant updates to EnergyPlus annually, testing the features according to the ASHRAE Standard 140 method. The following subsections describe the software tools tested in this research.

3.3.1 IESVE

Integrated Environmental Solutions Virtual Environment (IES VE) is widely used as a BPS tool for engineering and architectural firms involved in the design process of various national and international projects [29]. The Application for Air-Conditioning and Heating Engineers (APACHE), a Python-based application programming interface, is a simulation engine that has evolved into a friendly user interface for a detailed assessment and optimization of building energy performance and systems.

3.3.2 Design-Builder

Design-Builder calculates the energy consumption of the building and evaluates facade options to avoid overheating. In addition, it can calculate the impact of natural ventilation and infiltration, supply air distribution, and velocity distribution using computational fluid dynamics (CFD) [30], [31]. The results produce a large quantity of data according to the user's needs, compare different diagrams and give the possibility to evaluate the consequences of the changes. In the case of performing a CFD analysis, the program allows the users to understand the parameters of thermal comfort and indoor air quality [32].

3.4 Monitoring devices

An Elitech RC–51 Waterproof USB Temperature and Humidity Data logger was enclosed within the wigwam's canvas skin to collect the indoor relative humidity and temperature data points, with another being 20 feet away from the structure to measure outdoor temperature and relative humidity. The battery-operated device automatically logs this information every 5 minutes. It measures relative humidity from 10% to 95% and has an operating temperature range from −30°C to 70°C. The Data Logger's temperature accuracy is +/−0.5°C between −20°C and 40°C, and +/−1.0°C outside of this range, with the measured relative humidity accuracy being +/−3% RH at 25°C between 20% and 90% RH and +/−5% RH outside this range. Three rain gauges were used to measure and document precipitation. One was placed directly under the roof's opening inside the wigwam, another was placed directly next to the exterior of the wigwam, and the third was placed off to the side of the roof opening inside of the structure. A handheld anemometer was used directly outside and inside of the wigwam at various instances to measure and record air velocity at each fire event. In the CBE tool, the wind velocity was set to 0.1 m/s. The AWAIR device was used to monitor the indoor air quality of the wigwam. Being located within the wigwam's enclosed canvas skin, it was also used to record interior temperature, relative humidity, CO_2, $PM_{2.5}$, and VOC. Air tightness affects the indoor environment of this kind of shelter. According to other authors, infiltration values range from 0.6 to 1.4 ACH. The prototype has a low exposure to wind due to existing constructions. The software model's airtightness was established at a constant rate of 0.7 ACH throughout the year.

4 RESULTS

The weekly analysis is needed to compare actual and simulated data better. For this reason, the information has been collected to make the same week coincide with all the series to show a more appropriate comparison between the data.

4.1 Indoor and outdoor temperature and relative humidity (REAL)

Fig. 3 shows indoor and outdoor temperature and relative humidity were measured across the week of 18–25 December. The data showed that indoor and outdoor temperatures changed very similarly to each other without a fire. Temperature peaks mostly aligned with relative humidity troughs, and vice versa. When exposed to an enclosed fire, indoor temperatures rose higher and faster than outdoor temperatures, and relative humidity dropped lower and faster indoors compared to out. Similar results were recorded on 24 December for the open fire.

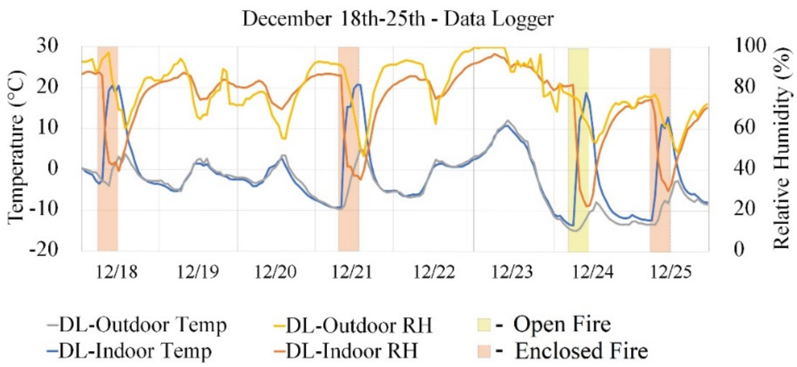

Figure 3: Indoor and outdoor temperature and relative humidity in a representative week in December. Results from the datalogger.

4.2 Indoor air quality (REAL)

The CO_2 concentrations in a representative week in December reached peaks up to 896.4 ppb, VOC and $PM_{2.5}$ concentrations reached magnitudes close and up to 5800 ppb and 1000 mg/m^3 during the open fire. An enclosed fire with a woodstove lowered the particulate matter concentration. The highest $PM_{2.5}$ concentrations for the first two enclosed fires was 118 µg/m^3, 195 µg/m^3, and 697 µg/m^3. As for the VOC, concentrations for the same enclosed fires reached 318, 332 and 391 ppb. These values could potentially create negative physical symptoms. The CO_2 concentrations for the enclosed fires rose with the particulate matter and achieved levels between 574.1 ppb and 713.1 ppb. Data collected during the open fire in December shows levels that are hazardous to human health. The CO_2 levels reached peaks up to 896.4 ppb, as it is shown in Fig. 4.

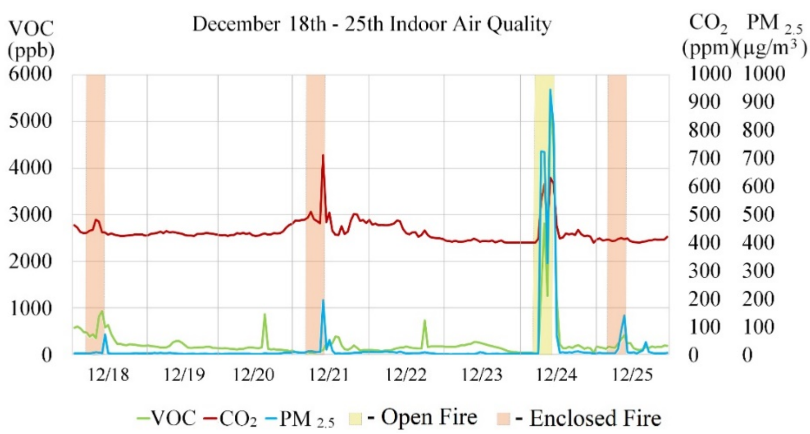

Figure 4: Pollutants concentrations in a representative week in December.

4.3 Simulation results: Indoor temperature and relative humidity

Because specific experimental values, such as solar radiation on inclined surfaces, were not measured, the verification process focused primarily on the indoor temperature and relative humidity. The location of the wigwam influenced the applied weather file in the Design-Builder software application, which was used as the default setting. The simulated indoor temperature values on 21 December exhibited matching trends and met the calibration criteria for the coefficient of determination. However, differences could be attributed to uncertainties in simulation inputs, including inaccuracies in the physical properties of the building and rates of infiltration or ventilation. There is a comparison between the experimental and simulated trends of internal air temperature and relative humidity during the experimental campaigns conducted in October and December. At peak heating load, the difference between the simulated and measured temperature was 10°C, while it reduced to 4°C when the hearths were turned off. Fig. 5 revealed that deviations in indoor relative humidity were more significant than temperature. The hourly temperature predictions had fewer errors, which was reasonable considering that relative humidity depended on additional factors such as soil, occupancy, and fuel combustion.

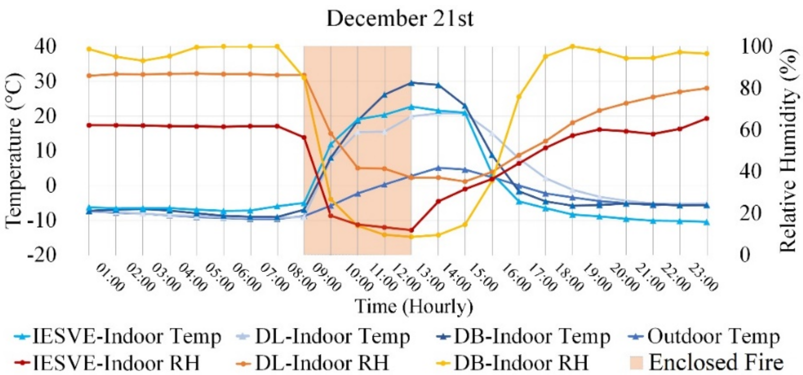

Figure 5: Pollutants concentrations in a representative week in December.

5 DISCUSSION

The outdoor temperature oscillations could lead to substantial differences between the real data and simulated values, and the envelope materials' conditions presented challenges on how they react to solar radiation, wind, and other outdoor conditions.

5.1 Indoor air quality with wood stove and open fire

This research compared the simulated models with field-measured data to assess their accuracy. However, the calibration process encountered various challenges. Firstly, the outdoor temperature data exhibited significant fluctuations, leading to potential discrepancies between the actual and simulated values. Secondly, the evolution of the building envelope over time introduced uncertainty as the materials underwent temperature variations. Lastly, simulating the heat source required creating a sensible heat load that increased temperature without adding humidity. Through field measurements, adjustments were made to different model parameters to achieve an acceptable error level. The digital model analyzed by Design-

Builder and IESVE incorporated a new method to simulate envelope parameters and characterize the heat source within the wigwam. After analysing the results, it became crucial to clarify the requirements for determining the accuracy of the building energy model. To consider the impact of the hearth when it was lit up, the first option was to use the occupancy with an equivalent heat load. However, that option increased the absolute humidity and, thus, changed the relative humidity of the indoor air. Therefore, a sensible heat load was loaded into the simulation with the same heat load as the wood used in the hearth at 375°C. The average amount of burnt wood for woodstoves was 2.1 kg per hour, whereas the average wood for open fires was 4.6 kg per hour. Fig. 6 illustrates that the fire was running for 5 hours per day, so the total amount of wood was 23 kg for open fires and 10.5 kg for wood stoves. As the weather grew colder, using open fires or a wood stove for short periods became necessary, resulting in increased indoor temperature, decreased relative humidity, and elevated pollutant levels. A hearth, modelled as a radiator using a Design-Builder assembly component, was placed at the centre of the wigwam. Its temperature was estimated to be around 100°C, and the indoor temperature of the wigwam was approximately 22°C when the hearth was lit. The relationship between indoor temperature and the levels of $PM_{2.5}$ and VOCs on 24 December and 25 December is shown in Fig. 6. The presence of a heat source during those days resulted in an increase in particle concentration and a decrease in relative humidity. The elevated concentrations of VOCs and $PM_{2.5}$ were primarily associated with open fires, inadequate ventilation, and occupants' lack of awareness regarding indoor air quality.

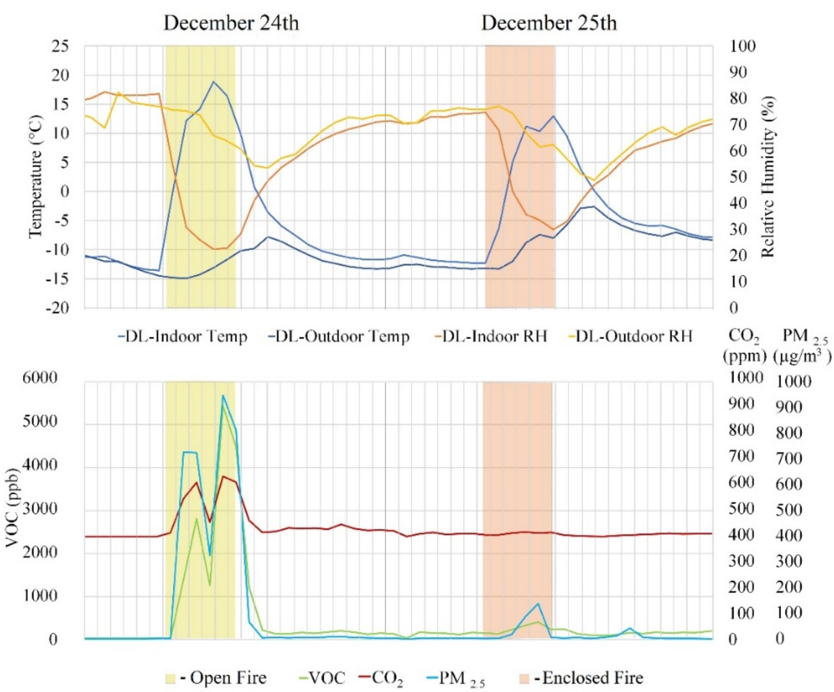

Figure 6: Temperature, relative humidity, and pollutants concentrations in a representative week in December.

Data collected during the open fire on 24 December indicated levels that posed health hazards. For instance, CO_2 levels peaked at 632.70 ppm, VOC levels reached a maximum of 5439.80 ppb, and $PM_{2.5}$ levels frequently rose to magnitudes close to or exceeding 947.80 µg/m^3 during the fire. Conversely, during enclosed fires VOC levels reached 409 ppb, which was not at dangerous levels but could potentially cause adverse physical symptoms. CO_2 concentrations during enclosed fires were around 416 ppm, representing a 34.40% reduction compared to open fire levels. Furthermore, $PM_{2.5}$ levels reached 139 µg/m^3 during enclosed fires, 85.33% lower than available fire levels but still above the 25 µg/m^3 threshold considered healthy. As the indoor temperature increased with each fire, a consistent pattern was observed among the indoor air quality variables. Having an enclosed fire influenced the amount of particulate matter emitted into the wigwam indoor environment, lowering the intensity of particulate matter. Analysing the $PM_{2.5}$ levels revealed that although significantly lower than open fires, the highest levels recorded for the first two enclosed fires were approximately 194 µg/m^3, exceeding the hazardous threshold of 25 µg/m^3. VOC levels during enclosed fires were also considerably higher than $PM_{2.5}$ levels, ranging from 137.60 ppb to 415 ppb. While these levels were not considered dangerous, they could cause adverse physical symptoms. CO_2 concentrations during enclosed fires increased in correlation with particulate matter and ranged between 407.70 ppm and 416.90 ppm.

The data collected during the open fires in December demonstrate levels that posed health risks to humans, including elevated CO_2 levels, VOC concentrations, and $PM_{2.5}$ magnitudes. The heat source's operation began at 08:30 on 17 December, previously being off. From 08:30 to 09:30, it operated at just 25% of its capacity, reaching a temperature of 79°C. Between 09:30 and 10:45, the temperature increased to 273°C. At noon, it reached its highest point of 370°C. Subsequently, as no additional wood was added, the temperature gradually decreased. From 14:00 to 24:00, the fire extinguished on its own.

5.2 Validation of the simulation results

This section aimed to assess the results from the simulation by comparing them with those delivered by the data loggers. In Design-Builder, the datalogger's climatic data were introduced into the software. In IESVE, the simulation data were selected among those that fit the outdoor conditions. Thus, the indoor air temperature and relative humidity were used to assess the accuracy of the simulated data using the NMBE and the coefficient of determination (R^2). Eqn (1) shows the NMBE that results from dividing NMBE by the mean of measured values, $\bar{A}$, and p is the number of parameters included in the control volume, which, for calibration purposes, is suggested to be zero.

$$\mathrm{NMBE} = \frac{1}{\bar{A}} \frac{1}{(n-p)} \sum_{i=1}^{n} (A_i - S_i) \times 100, \tag{1}$$

where A_i represents the actual data measured, S_i is the data simulated by the tools, and n is the number of samples. Finally, eqn (2) shows the expression of the coefficient of determination, R^2. It is another statistical index commonly used to measure the uncertainty of the models. It is limited to between 0.00 and 1.00 where the upper value indicates that the simulated values correspond to the measured ones correctly and the lower ones do not. It is not a prescriptive value for calibrated models, but the ASHRAE Guideline 14-2014 always recommends values above 0.75 for hourly measurements.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(A_i - S_i)^2}{\sum_{i=1}^{n}(A_i - \bar{A})^2}. \quad (2)$$

This section aimed to demonstrate a good correlation between the actual data of the indoor temperature and relative humidity and the simulated values. The digital model created by Design-Builder and IESVE included a new methodology to consider the envelope parameters and the heat source inside the wigwam. Thus, after examining the results, it was necessary to define the accuracy of the building energy model. The calibration criteria evaluate the simulated values against actual measurements. Table 1 illustrates the indices used to calibrate errors and the thresholds proposed by the ASHRAE Guideline 14. The calibration criteria given by these standards are ±10% for the NMBE, and >0.75 for the coefficient of determination R^2. IESVE temperature simulation results showed a better performance, whereas Design-Builder relative humidity values were slightly more accurate.

Table 1: Error calibration indexes according to ASHRAE Guideline 14.

Index	**ASHRAE 14**	**DB tint**	**DB RH**	**IESVE tint**	**IESVE RH**
NMBE	±10	0.38	17.60	0.32	19.75
R^2	> 0.75	0.83	0.70	0.87	0.68

The NMBE and R^2 were calculated considering hourly data from dataloggers and simulation software. The results of hourly calibration against the ASHRAE criteria show the deviation assuming hourly data for a 1-month simulation. The deviation range for NMBE and R^2 values were below 15% and 5%, respectively for December, which meant a good match between the prototype measurements and simulation values.

The simulated indoor temperature data obtained through the digital models showed a good correlation in all the comparisons made against the measured data from the prototype. The coefficient of determination (R^2) between observed and simulated indoor air temperature changed as a function of the indoor data of all the considered testing periods is consistently above the calibration criteria (>0.75) accepted by ASHRAE. On the other hand, the relative humidity values indicated an R^2 value far from the model's predictions. The errors grew as the indoor temperature increased. In all cases, the hearth's peak of thermal load delivered the most significant difference between measured and simulated data. From 20 December to 26 December, the simulated indoor temperature approximated the measured values and satisfied the required calibration criteria for the coefficient of determination.

6 CONCLUSIONS

This research's newness is the result of comparing energy simulation and actual measurements to assess indoor air quality and renewable fuel consumption for Native American shelters. The collected measurements showed the capacity to achieve comfort within the shelter in cold outdoor weather conditions in New England, US. However, the indoor air pollutants were far from acceptable concentrations when open fires were used to warm up the shelter. Measurements collected in December showed VOC, $PM_{2.5}$, and CO_2 concentrations hazardous to human health. For example, the CO_2 levels reached 560 ppm, VOC levels peaked at 5439.80 ppb, and $PM_{2.5}$ levels reached magnitudes close and up to 860 μg/m^3 multiple times during the fire event. In contrast, during closed fires, the VOC levels reached 391 ppb, not at dangerous concentrations but with the potential to produce adverse physical symptoms. The CO_2 concentrations for the enclosed fires achieved levels of 600 ppb, 30% below open fire levels. There is room for improvement in the suggested

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methodology. First, the mean radiant temperature was not measured. Design-Builder provides users with operative temperature, so those values can be used as input to calculate thermal comfort. However, it would be more reliable if the temperature of the heat source and the envelope were considered. Future research must include envelope temperature measurements to estimate the heat source radiation's impact accurately. Second, the prototype was studied in the cold season. Validating the model in other seasons with different envelopes is a future challenge. Third, it is essential to find a renewable heat source that does not negatively affect the indoor air quality of the occupants.

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