

Chapter 4

Learning from the Past for a Sustainable Future: Environmental Monitoring and 3D Modelling to Assess the Thermal Performance of Heritage Buildings



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Abstract There are numerous lessons to be learned from historic buildings, such as the rich diversity of their traditional architecture, the use of natural and local materials, their durability and resilience, or because they allow for thermal comfort in severe climatic and weather conditions. Today, many of these heritage buildings are still standing and in use, but their shape may have changed significantly from when they were built. In this sense, to accurately analyse historic buildings, 3D models that approximate their geometry (as-is/as-built models) must be produced. Based on terrestrial laser scanning 3D point clouds, as-is 3D modelling can represent the geometrical alterations of the assets to enable diverse analyses and simulations. This work addresses Ye Olde Trip to Jerusalem building, claimed to be the oldest inn in England, UK (1189 AD). Hence, this historic building presents numerous deformations such as warped and tilted walls, recess in walls, non-planar ceilings, and an irregular arrangement of bent ceiling beams. This Grade II listed building is located near Nottingham Castle, beneath Castle Rock, the natural promontory on which the castle is situated. A part of the inn is inside rock-hewn caves under Castle Rock, making it a unique landmark with special indoor thermal conditions.

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Due to the complex geometry of the building, laser scanning-based 3D modelling is found essential to communicate the building's features to help understand its thermal behaviour. This paper aims to investigate how Ye Olde Trip to Jerusalem building is capable of regulating indoor temperature and humidity in different locations, for which the as-is 3D modelling and environmental monitoring of this historic building are discussed. Based on the findings, the lessons learnt from studying old buildings could be utilised to enhance the sustainability of modern buildings.

Keywords 3D scanning · Geometrical alterations · Sustainability · Thermal comfort · Historic buildings

4.1 Introduction

There are numerous lessons to be learned from historic buildings, such as the rich diversity of their traditional architecture, the use of natural and local materials, their durability and resilience, or because they allow for thermal comfort in severe climatic and/or weather conditions [1–3]. Today, many of these heritage buildings are still standing and in use, but their shape may have changed significantly from when they were built. In this sense, to accurately analyse these assets, 3D models that approximate the geometry of historic buildings—so-called as-is or as-built models [4]—must be produced. Based on terrestrial laser scanning 3D point clouds, as-is 3D modelling can represent the geometrical alterations of the assets. This enables diverse analyses and simulations.

However, current modelling and analysis of historic buildings are usually based on ideal or excessively simplified geometries [5]. This includes non-deformed 3D models generated from traditional measurement methods data; also, those models developed using Terrestrial Laser Scanning (TLS) point clouds as a reference to create the 3D objects defining the buildings instead of implementing some degree of automation to use those spatial data to represent the geometrical alterations of the buildings. Antón et al. [6] described that the 3D models produced may not represent the real condition of these assets, their features, and/or singularities. Furthermore, the analysis outcomes may not fully represent the actual performance of these heritage assets if those geometrical alterations are not modelled.

This work addresses the case study of the Ye Olde Trip to Jerusalem building, claimed to be the oldest inn in England (UK), dating back to 1189 AD. Therefore, this historic pub presents numerous and significant deformations such as warped and tilted walls, recess in walls, non-planar ceilings, and an irregular arrangement of bent ceiling beams. This Grade II listed building [7] is located near Nottingham Castle, beneath Castle Rock, the natural sandstone promontory on which the castle is situated. A part of the inn is inside rock-hewn caves under Castle Rock, making it a unique landmark with special indoor thermal conditions.

Research has been found that there are many lessons to be learnt from heritage buildings towards future sustainability in modern buildings [8, 9]. This paper aims to assess the thermal regulations of different sections of the building and the way they can regulate indoor temperature and relative humidity with particular interest to the cave section, for which the as-is 3D modelling and environmental monitoring of this historic building are discussed.

The rest of this paper is organised as follows: the methodology is described in Sect. 4.2, comprising the approach, equipment, and statistical analysis for the thermal performance assessment; the as-is 3D modelling approach is also explained. Next, Sect. 4.3 presents and discusses the modelling results and the temperature (T) and relative humidity (RH) data from the sensors installed. The conclusions of this research are drawn in Sect. 4.4.

4.2 Methodology

With a view to assess the thermal performance of Ye Olde Trip to Jerusalem building, ambient temperature and humidity sensors were used, see Fig. 4.1. This environmental monitoring characterises the indoor and outdoor hygrothermal conditions of this singular heritage building, thus revealing users' comfort inside. To do this, three OMEGA temperature and humidity data loggers (OM-CP-RHTEMP101A) were used. As shown in Fig. 4.1c, two were installed inside the building: the first (ID 1_Cave) was attached to the cave wall in the top-floor room; the second sensor (ID 2_ColdRoom), was in the downstairs room (with three walls facing the exterior) of the highest body of the building. The rooms monitored were not cooled nor heated. Finally, the third sensor (ID 3_Exterior) was installed outside, under the roof eaves, and protected from direct sunlight, wind, and rain. The thermal monitoring details were as follows:

- Start date and time: 24/06/2022; 10:30 am.- Duration: 14 days
- End date and time: 08/07/2022; 10:30 am. - Reading interval: 15 min.

Next, in order to compare the data from the three sensors, and thus characterise the rooms against each other and the exterior, statistical data were calculated from the temperature and humidity values. This included the maximum, minimum, and average values; the distribution analysis through the standard deviation and the coefficient of variation (standard deviation divided by the mean); and the covariance, and correlation coefficient to evaluate the relationship between the two variables (temperature and relative humidity).

In relation to the as-is 3D modelling of Ye Olde Trip to Jerusalem building, TLS technology was first used to record the geometry of this case study. The 3D survey

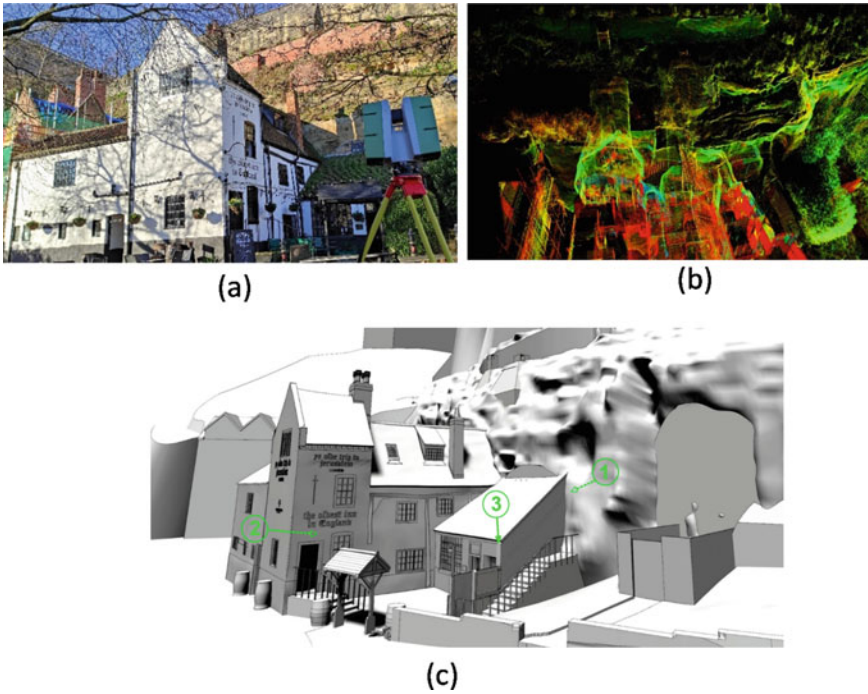


Fig. 4.1 a Photograph of Ye Olde Trip to Jerusalem and TLS device; b 3D point cloud data with intensities; c As-Is 3D model with installed sensors

consisted of 31 stations (or scan positions) throughout the building and its surroundings, strategically set to avoid laser beam occlusions. The scanning resolution was set to 6 mm at 10 m. Following the recording, the 31 individual clouds were (1) automatically registered, i.e., aligned and merged in the same global coordinate system through cloud constraints set in Leica Cyclone software, (2) segmented to remove noise and undesired elements, and (3) subsampled to 20 mm to ease data processing. Later, GPS data were collected to geo-reference the global 3D point cloud.

Once the data were obtained, the as-is 3D modelling took place. To do this, manual and semi-automatic processes were implemented to create its building components. This was achieved by using the point clouds in CloudCompare software to produce 3D polygon meshes defining the cave surface. To build warped walls and other large, deformed components, Rhinoceros software was used to (1) create non-planar surfaces automatically fitting the building's wall faces point clouds, (2) ensure a close volume defining the wall shape, and (3) producing a solid object from it. Finally, extruding planar surfaces from contours also produced solid objects.

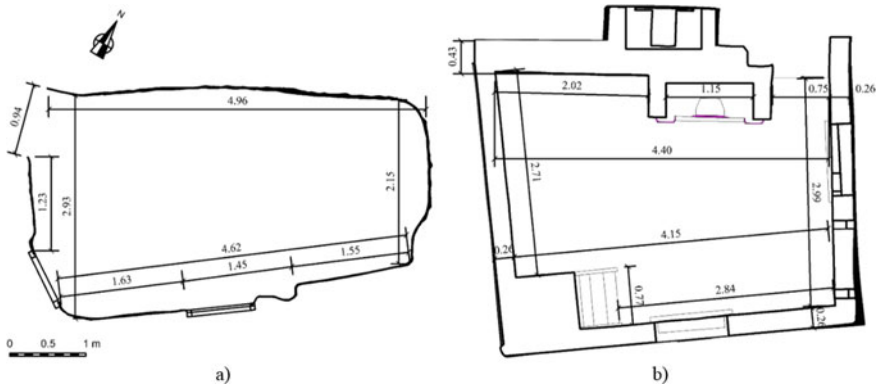


Fig. 4.2 Floorplans: **a** cave room upstairs (sensor 1); **b** cold room downstairs (sensor 2)

4.3 Results and Discussion

4.3.1 As-Is 3D Modelling

Focusing on the digital reconstitution of the case study, Fig. 4.1 shows the combination of the manual and semi-automatic approaches to produce its as-is 3D model. The location of each sensor is also indicated in the image above. The level of detail of the surroundings is lower than that of the inn so that the computational resources in 3D visualisation are reduced. After all, the building's geometry was given greater importance.

Despite a thoroughly planned 3D survey, furniture, and decorative elements inside and outside the building implied laser beam occlusions. As a result, the 3D point cloud presented certain gaps (lack of points) that did not allow for 3D meshing all wall faces and ceilings. Consequently, the creation of best-fit non-planar surfaces led to represent the geometrical alterations of this heritage building. The as-built 3D modelling enabled accurate measurements of each room. Figure 4.2 displays the floorplan of each room monitored as indicated in Fig. 4.1. The volume of the rooms is 31.79 m^3 and $29.30 \pm 1.1 \cdot 10^{-5} \text{ m}^3$, respectively.

4.3.2 Environmental Monitoring

The three OMEGA sensors collected 1345 temperature and relative humidity (two channels) recordings each in the time interval set (14 days). Graphs displaying the data from sensors 1, 2, and 3 are given below (see Figs. 4.3, 4.4, and 4.5).

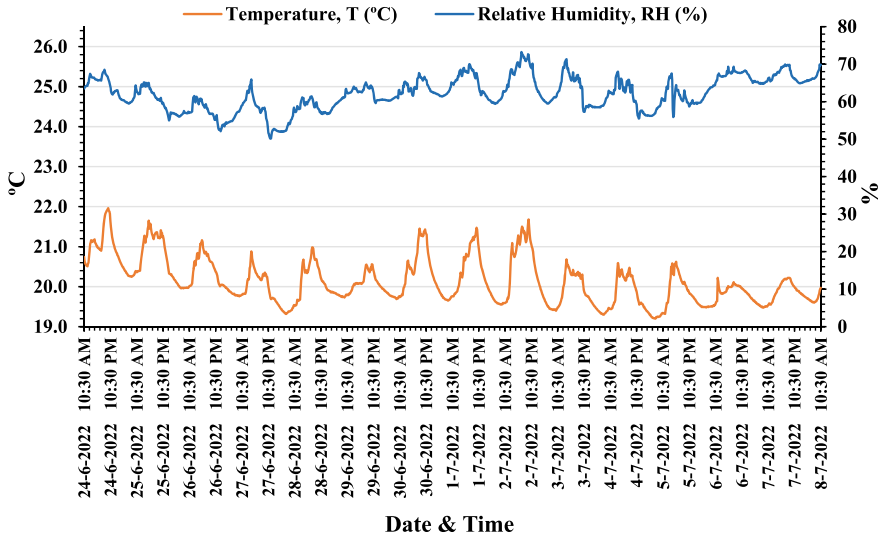


Fig. 4.3 Temperature and relative humidity from sensor 1 (The cave section)

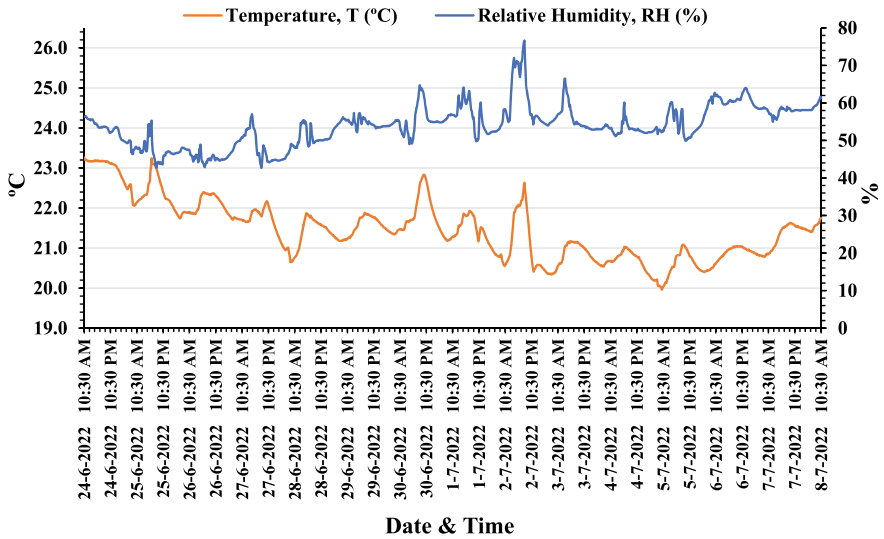


Fig. 4.4 Temperature and relative humidity from sensor 2 (The cold-room)

It is worth noting that building occupation was not considered, although the inn's opening and closing time was from 11am to 11 pm from Monday to Sunday, which may have an impact on the data. The statistical data from the sensors' recordings are presented in Table 4.1, where the highest values appear in bold for clarity.

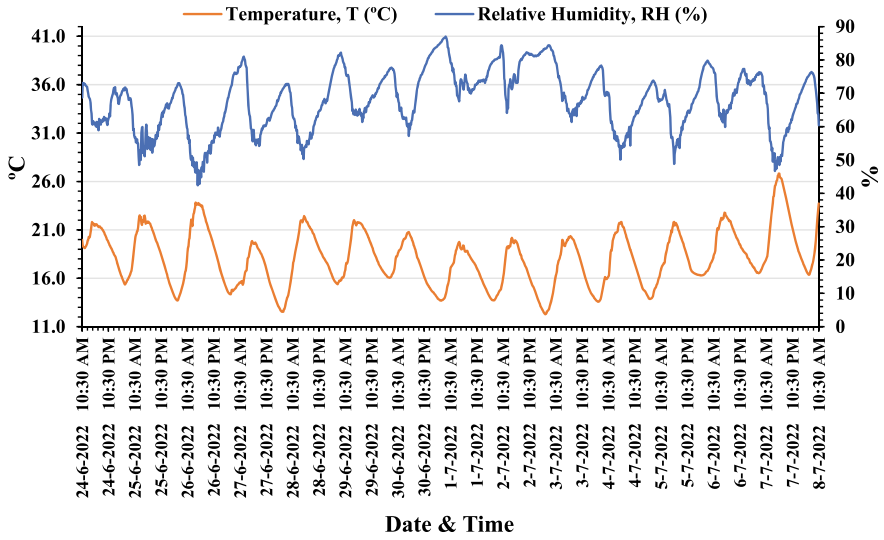


Fig. 4.5 Temperature and relative humidity from sensor 3 (exterior)

Table 4.1 Sensors 1 (the cave), 2 (the cold-room), and 3 (the exterior) temperature and relative humidity statistics

	Maximum	Minimum	Average	Standard deviation	Coefficient of variation	Covariance	Correlation coefficient
<i>Sensor 1</i>							
T (°C)	21.96	19.20	20.14	0.5693	0.0283	0.9156	0.3708
RH (%)	73.20	50.10	62.08	4.3376	0.0699		
<i>Sensor 2</i>							
T (°C)	23.26	19.96	21.45	0.7369	0.0344	- 0.8925	- 0.2247
RH (%)	76.60	42.70	53.87	5.3902	0.1001		
<i>Sensor 3</i>							
T (°C)	26.82	12.29	18.07	2.8218	0.1561	- 19.0773	- 0.7542
RH (%)	87.00	42.40	68.11	8.9641	0.1316		

The graphs show a more uniform behaviour of *sensor 1* against *sensor 2* during the temperature and humidity monitoring. The former sensor detected a lower temperature curve than the latter, but a higher relative humidity. *Sensor 3* also provides uniform data, and a higher amplitude (minimum–maximum values) of each 24-h cycle (day and night) since the device recorded (more extreme) outdoor conditions.

The hygrothermal performance of the selected rooms of Ye Olde Trip to Jerusalem can also be quantified. Firstly, mentioned should be made to absolute and relative minimum and maximum values during the monitoring period. *Sensor 1*, always below 22 °C, exceeds 21.5 °C on three days (21.43%), whereas *sensor 2* is over that temperature 71.43% of the cycles (10 days). Focusing on minimum values, *sensor 1* is below 20°C for 92.86% cycles (13 days), but *sensor 2* reaches that point only on 5–7–22 (10 am). The average T of *sensor 2* is 6.5% higher than that of *sensor 1*, whereas the mean RH of the latter is 15.24% higher. *Sensor 1* exceeds 60% RH (relative maximum values, cycles) during the monitoring period in 921 recordings (68.48% of the total). In contrast, *sensor 2* reaches that point in 158 recordings (11.75%).

Secondly, the distribution of the sensor data is worth examining. Both the standard deviation and the coefficient of variation indicate a lower dispersion of the data from *sensor 1*, which makes the cave area of Ye Olde Trip to Jerusalem present lower variable indoor temperature and relative humidity values against the other (more exposed) room and the exterior (the latter being in bold).

Finally, the relationship between the temperature and relative humidity should be evaluated. The cave's (Table 4.1) positive values (in bold) of the covariance and correlation coefficient clearly show that both variables jointly increase and decrease (direct relationship) during the monitoring, according to the graph in Fig. 4.3. In Fig. 4.4 and Table 4.1 (*Sensor 2*), this is not that constant since the behaviour is more variable and represents an overall negative relationship. The values in Fig. 4.5 and Table 4.1 (*sensor 3*) indicate a strong, inverse relationship between the two variables; when the temperature increases, the relative humidity decreases.

4.4 Conclusion

This paper proves that modelling of complex geometrical features of heritage buildings allows for accurate representation, which has an impact on the accuracy of measurements if the as-is condition is achieved. It also supports understanding of the building structure and its influence in the hygrothermal behaviour. 3D laser scanning and modelling of physical structures will support the creation of Digital Twins (DTs) to accurately preserve the heritage building in a digital format and allow for integrating simulation data in the virtual model.

In this work, the calculation of selected room volumes of Ye Olde Trip to Jerusalem was conducted to provide the environmental monitoring geometrical conditions. Given the irregular shape of the cave surface and warped walls, these measurements would be less accurate if following a non-as-is 3D modelling approach.

Regarding the hygrothermal performance assessment of those selected rooms, statistical data demonstrated that the cave area can regulate indoor temperature and relative humidity against the downstairs room (building) in response to exterior change in environmental conditions.

Further work will address the integration of sensor data into as-is models. Thus, benefiting from a more accurate geometry, heat flow, surface pressure, and humidity simulations, among others, can be carried out to precisely evaluate the behaviour of heritage buildings.

Acknowledgements This work has been funded by the England European Regional Development Fund (ERDF) (reference 08R20S04177) as part of the European Structural and Investment Funds Growth Programme 2014-2020, the University of Nottingham and Nottingham Trent University through the Live Experiential and Digital Diversification - Nottingham (LEADD:NG) project. Special thanks to Karl Gibson for granting access to Ye Olde Trip to Jerusalem and easing the surveys; also, to Sherna Salim for supporting sensor settings. This work has also been supported by funding for a post-doctoral researcher contract from the VI Plan Propio de Investigación y Transferencia of Universidad de Sevilla (reference VIPPIT-2020-II.5), Spain.

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