

# Impact of climate change on sustainable production of Sherry wine in Nearly-Zero Energy Buildings

## Abstract

Wine is the main economic resource in the 'Area of Jerez', located in the south of Spain. It is one of the most important wine tourism destinations in the world. However, its sustainable production process, so strongly influenced by climatic conditions, can be clearly affected by the phenomenon of global warming. The ageing process of "Sherry wine" takes place in buildings known as 'Cathedral warehouses', an example of Nearly-Zero Energy Buildings (NZEBs). For centuries, they have been used to provide specific ecological conditions for biological ageing without any type of mechanical heating/cooling system. The purpose of this paper is to assess the impact of climate change on this production model. For this, the annual thermal behavior of a representative winery was monitored during several years. The first energy simulation model of this type of buildings was developed and validated (daily  $R^2 = 99\%$ ; hourly  $R^2 = 97\%$ ). Finally, the model was simulated by modifying the outdoor climatic conditions (9 years training data sets) for a climate change scenario, applying the 'morphing' method for the transformation of the weather data. The results show that, by the middle of this century, the average outdoor temperature will increase by 2.3 °C (in summer up to 3.6 °C). As a consequence, the temperature in the ageing zone would exceed the comfort limit for 19% of the year, (up to 34% in hot years). For 2080, the prediction is even worse (average value of 27%). As a result, the microorganisms responsible for this unique process could not maintain their activity. This fact will force the sector to face a harsh reconversion through the adoption of new mechanisms and strategies, which endangers the economic sustainability of an entire region dedicated to this practice. Beyond the specific case, the work highlights the need to evaluate the future behavior of NZEBs through simulation.

**Keywords:** Climate change; Sherry wine; biological ageing; Zero Energy Building.

## 1 Introduction

On the western coast of the region of Andalusia (Spain) the world-famous “Sherry wines” are produced (BOJA, 2013). Wine is the main economic resource in the “Area of Jerez” (López-Guzmán et al., 2014). Its historical and cultural heritage make it one of the most important wine tourism destinations in the world, receiving more than 500,000 visitors a year (ACEVIN, 2019). However, its particular production process, so strongly influenced by climatic conditions, can make it clearly affected by the phenomenon of global warming.

The ageing process takes place in unique buildings known as “Cathedral warehouses”. These constructions, some of them centuries old, provide the specific ecological conditions for biological ageing. These conditions are necessary for the proliferation of a yeast layer which grows on the surface of the wine, called “veil of flor” (Jackson, 2008). Biological ageing requires very limited thermal conditions, in addition to an abundant presence of oxygen, that implies constant ventilation of the cellars (Suárez Lepe, 2004). When these environmental conditions change, this biological process is seriously affected (Mazarrón et al., 2012).

Almost 50 % of European Union (EU) final energy consumption is used for heating and cooling, of which 80 % is used in buildings. In this regard, the EU has proposed to achieve a highly energy efficient building stock and to ensure that the long-term renovation strategies deliver the necessary progress towards the transformation of existing buildings into Nearly-Zero Energy Buildings (NZEB) (EU, 2010, 2018). The search for construction strategies that allow the reduction of air conditioning needs, while maintaining adequate levels of comfort, is one of the greatest challenges of modern construction with great potential for development in the coming decades. In this sense, the “Cathedral warehouses” are a good example of NZEB, since they provide the thermal comfort necessary for biological ageing without any type of heating/cooling system. However, its effectiveness could be compromised in the coming decades.

49 According to the Intergovernmental Panel on Climate Change (IPCC) the global increase of the  
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250 temperature between the average of the 1850–1900 period and the 2003–2012 period was 0.78 °C  
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51 (Stocker, 2013), over 1 °C above for 2017, and increasing at 0.2 °C per decade. It is likely that within the  
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752 next 20 years, the global warming temperature will be 1.5 °C higher above pre-industrial levels (Allen,  
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953 2018). But this impact could be particularly severe in south European countries like Spain (Giorgi and  
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1254 Lionello, 2008). According to the Spanish meteorological agency (AEMET), for the year 2020 the increase  
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1455 in the average temperature in Spain was 1.7 °C higher than the pre-industrial period, and this value  
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1656 increases at a rate of 0.3 °C per decade and accelerating (AEMET, 2021).

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2057 Since building performance is strongly related to weather conditions (Zou et al., 2021), there is a  
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2258 challenge of designing sustainable low-energy buildings, which allow providing thermal comfort under  
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2459 warmer summer conditions produced by climate change (Holmes and Hacker, 2007).

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2860 The interest of the scientific community for the biological ageing of “Sherry wine” is significant, there  
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3061 are dozens of publications on the physical-chemical properties of this unique product (Valcárcel-Muñoz  
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3262 et al., 2022) (Marcq and Schieberle, 2021) (Schwarz et al., 2021), genetic studies of the yeasts that  
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3563 produce them (Carbonero-Pacheco et al., 2022) (Kishkovskaia et al., 2021) (Eldarov et al., 2018),  
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3764 economic aspects (Foronda-Robles, 2018), commercial aspects (Cruces-Montes et al., 2020) (Rodríguez-  
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3965 Garcia and Vieira-Rodríguez, 2017), etc. In contrast, studies that analyze the indoor environment of the  
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4266 constructions that allow these processes are scarce (Navia-Osorio et al., 2022) (Canas et al., 2014).

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4567 Given the pessimistic forecasts of the effects of climate change, and bearing in mind the demands of  
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4768 biological ageing, this article analyzes whether the “Cathedral warehouses” will continue to be an  
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5069 example of NZEB in the near future, or if on the contrary, the current production model could be  
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## 2 Methodology

The thermal behavior of a winery was monitored for several years. Subsequently, an energy simulation model of the building was developed. This model was validated through Measurement and Verification protocols for an existing building (Webster et al., 2015). Once verified, the model was simulated in a period of nine years by modifying the outdoor weather conditions in a climate change scenario. Future weather conditions were obtained through “morphing methods”. Finally, the limits of the thermal comfort conditions necessary for biological ageing were established.

### 2.1 Case study

For this study, a winery was selected where one of the most prestigious international wines with “protected designation of origin” (“Manzanilla” sherry) is produced (BOJA, 2013). Located in the town of Sanlúcar de Barrameda, on the Atlantic coast of Andalusia (Spain), in the area known as “El Marco de Jerez” (area of Jerez) (Figure 1).

Figure 1. Location of the research area: “El Marco de Jerez” (area of Jerez)

Sanlúcar de Barrameda has a Mediterranean-Oceanic climate with moderate temperatures throughout the year. The mean annual temperature in the study year was 18 °C, with maximum temperatures around 38.6 °C in July and minimum temperatures of 3.6 °C in February. Air humidity is quite high, except in the dry months, with an average annual relative humidity of 68%. The annual average insolation reaches values higher than 3,000 h/year.

The winery, built at the end of the nineteenth century, has a simple architectural structure (Figure 2), composed of a large open-plan rectangular space, 71 m long and 33 m wide, with the main axis 33° oriented toward the northwest. The gabled roof has a 24° angle of inclination. The height of the lateral

walls is 7 m and the height under the roof is 14.5 m. Inside the warehouse, the “ageing zone”, where product is stored, is reduced to the first four meters from the floor (Figure 3).

Figure 2. Artistic 3D representation of the winery under study.

Figure 3. Interior section of the winery, showing the area where the wine is aged.

The 60 cm thick external walls are made with masonry from a highly porous local sedimentary rock known as “ostionera stone”, on which mortar plasters were applied and whitewashed. The roof is composed of Arabic tile (baked clay), with a mortar seat, on a 5 cm thick rough calcareous brick, which in turn rests on a pine wood structure (Figure 4).

Figure 4. Construction characteristics of the winery envelope: floor, walls and ceiling.

The side walls (west and east) have a series of windows, 10 to the west and 11 to the east, all of them 2.50 m wide by 1.70 m high, located 4 m from the ground (above the ageing zone). The windows do not have glass, instead they have wooden lattices (Yravedra Soriano, 2003) that prevent the entry of natural light and air currents, but remain open most of the year allowing the constant diffusion of oxygen. The west wall also has two 4x2 m doors, made of pine wood, with openings in the upper part of 2x1 m dimensions, with characteristics similar to the main windows.

The south wall has five windows, four of 4x2 m, 1.50 m from the ground and one of 2x1.7 m, 4.5 m from the ground. The north wall has five windows of 3.5x2 m, 1.5 m from the ground. In both, the north and south walls, there are two circular openings, similar to rosettes, 3 m in diameter, and located 8.50 m from the ground, under the roof. The windows on the south wall remain closed most of the year.

118 The warehouse does not have any type of insulating pavement from the ground, it only has a layer of  
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219 “albero” (silty-sandy soil) on the natural ground and service corridors with a small 10 cm layer of  
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120 concrete to facilitate operations. The building does not have any heating/cooling system.  
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## 122 **2.2 Monitoring system and validation data**

123 A monitoring plan was designed by installing temperature sensors that were distributed in different  
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124 areas of the interior and exterior of the building (Figure 5). The objective of the monitoring plan was to  
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125 detail the thermal behavior of the winery throughout the year.  
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126 Figure 5. Location and height of the sensors installed inside the winery.  
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128 To determine horizontal temperature variations, four sensors were installed at different locations (P1,  
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129 P2, P3, and P4). The sensors were placed at an intermediate product storage height (1.8 m) in the ageing  
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130 zone. In order to monitor vertical variations in detail, numerous temperature sensors were installed in  
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131 the central area of the winery (P2 and P3). To do this, the probes were placed at different heights  
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132 between 0 and 11.3 m, covering a large part of the vertical profile from the ground to the area near the  
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133 roof. The external temperature was monitored through a sensor located near the building (Pout),  
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134 protected from solar radiation and rain with a housing designed for this purpose.  
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135 During the monitoring process was used five Hobo® Pro V2 data loggers with interior thermistor-type  
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136 temperature sensor (precision  $\pm 0.18$  °C at 25 °C) and two channel Hobo® data-loggers with exterior  
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137 temperature probes (precision  $\pm 0.25$  °C at 20 °C and resolution 0.03 °C at 20 °C). The measurement  
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138 interval was set at 15 min for all the loggers for one year. Thus, 630,720 indoor data and 35,040 external  
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139 data are available for each year.  
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140 The winery was monitored for four years. The evolution of the interior temperature during this period  
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141 was similar, with an average standard deviation between years of 1.4 °C and differences in annual  
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142 maximum temperature of less than 2 °C. Unfortunately, problems with the sensors (such as the theft of  
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143 the external sensor) affected the second and third year of data, leaving only two full years (1<sup>st</sup> and 4<sup>th</sup>)  
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144 for model validation and characterization of indoor temperature.  
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145 To demonstrate the representativeness of the outdoor temperature monitored, data from a  
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146 climatological station located in the same town, published by a local government (IFAPA, 2022), have  
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147 been used. The weather station was only operational from 2004 to 2011 (2010 incomplete).  
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148 Nevertheless, this historical series serves the mentioned purpose.  
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### 18 19 20 21 150 **2.3 Development of the building energy simulation model (Input data)** 22 23

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151 The building was modeled using building energy simulation program called EnergyPlus™ using as  
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152 interface DesignBuilder® software version 7.0.0. In this model, the existing architectural elements were  
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153 included (Figure 6).  
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154 Figure 6. Representation of the building model in DesignBuilder®.  
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156 For the simulation, the following parameters were entered:  
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157 • “Location”: site location (latitude 36.78; longitude -6.35), ASHRAE climate zone (3A), elevation  
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158 above sea level (12 m) and site orientation (327°).  
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159 • The temperatures of the ground surface, for each month, were calculated from the monthly  
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160 average of the temperatures collected by the sensors located at 0 m.  
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161 • A specific EnergyPlus Weather data file (EPW) was generated from the outside sensor data  
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162 collected.  
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163 • The building enclosures (external walls and pitched roof) were programmed from the CTE WEB  
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164 materials library (CTE, 2021) as shown in Table 1.  
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166 Table 1: Thermal values of the enclosures used in the proposed model.  
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169 **2.4 Validation model**

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370 The model obtained was validated based on the recommendations proposed by the Federal Energy  
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171 Management Program (FEMP) (Webster et al., 2015) and the American Society of Heating, Ventilating,  
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172 and Air Conditioning Engineers (ASHRAE, 2014). In both cases, the principal error estimation indices  
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173 used are: Normalized Mean Bias Error (NMBE) (Equation 1), Coefficient of Variation of the Root Mean  
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174 Square Error [CV(RMSE)] (Equation 2) and coefficient of determination ( $R^2$ ) (Equation 3) (Ruiz and  
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$$NMBE = \frac{\sum_{i=1}^n (m_i - s_i)}{\sum_{i=1}^n m_i} \times 100 (\%) \quad (1)$$

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$$CV(RMSE) = \frac{1}{\bar{m}} \sqrt{\frac{\sum_{i=1}^n (m_i - s_i)^2}{n}} \times 100 (\%) \quad (2)$$

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$$R^2 = \left( \frac{n \cdot \sum_{i=1}^n m_i \cdot s_i - \sum_{i=1}^n m_i \cdot \sum_{i=1}^n s_i}{\sqrt{(n \cdot \sum_{i=1}^n m_i^2 - (\sum_{i=1}^n m_i)^2) \cdot (n \cdot \sum_{i=1}^n s_i^2 - (\sum_{i=1}^n s_i)^2)}} \right)^2 \quad (3)$$

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3179 Where:  $m_i$  = the measured value of temperature;  $s_i$  = the simulated value of temperature;  $\bar{m}$  =  
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3380 mean value of measured temperature; and  $n$  = the number of measured data points.

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181 The model has been validated using hourly and daily averages calculated from the data monitored  
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3982 during the two years previously mentioned. Thus, the error estimation indexes have been calculated on  
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4183 an hourly and daily scale.

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485 **2.5 Future weather data**

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5186 The IPCC in the Special Report on Emissions Scenarios (SRES) describes four scenarios (A1, A2, B1 and  
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187 B2) based on future greenhouse gas (GHG) emissions (Nakicenovic and Swart, 2000).

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188 To assess the effects of climate change, it is necessary to have a prediction model of future weather  
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589 conditions. For this purpose, a Microsoft® Excel based tool has been used called “The climate change

190 world weather generator” (CCWorldWeatherGen) (Jentsch et al., 2017), this tool is based on ‘morphing’  
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3 methodology for climate change transformation of weather data (Belcher et al., 2005). This application  
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5 allows you to transform EnergyPlus Weather data files (EPW) into EPW under climate change conditions  
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7 for three-time intervals: 2020, 2050 and 2080, according to the predictions of the Hadley Center Climate  
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9 Model (HadCM3) for a medium-high emission scenario (A2) (Jentsch et al., 2013).

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12 In this regard, it should be noted that Touhami et al. (2015) in their study on the impact of climate  
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14 change on an aquifer, located in a semi-arid zone of south-east Spain, studied the three General  
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16 Circulation Models (GCM) most used in the European region from the IPCC Data Distribution Centre  
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18 (DDC) (IPCC, 2021) and determined HadCM3 as the most representative GCM of the climatic conditions  
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20 (historical and future data) at the study site.

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23 The historical series of outdoor temperature (from 2004 to 2011, except 2010), together with two years  
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25 of monitored data, have been used to carry out an ensemble of several training data sets. As a result,  
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27 the effect of climate change on indoor comfort has been analyzed based on 9 different years (9 different  
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29 climatological files).

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206 This study aims to determine the time that the thermal conditions inside the winery are within the  
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208 comfort ranges, in order to identify the periods of potential risk for the correct ageing of the wine. In  
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210 this sense, several authors point out that the range of limit temperatures for the development of the  
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212 yeasts that produce Sherry wines is between 10 and 25 °C, (Marcilla, 1936) (García del Barrio Ambrosy,  
1984) (Jl Lozano and Perdigones, 1989) (Barbadillo, 1993) (Bravo Abad, 1995) (Suárez Lepe, 2004).  
Crues (1946) in laboratory tests carried out in California on twelve strains of flower yeast concluded  
that at the temperature of 68-70 °F (20 °C) all cultures formed adequately veil; however, in general, they

213 could not maintain their activity at temperatures above 26.6 °C (80 °F). Therefore, it is assumed that the  
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214 temperature limits for yeast development are between 10 and 26.6 °C.

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### 216 **3 Results and discussion**

#### 11 **3.1 Characterization of indoor temperature from monitored data**

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To carry out a correct design and validation of the model, it is essential to characterize in detail the evolution of the indoor temperature and the response of the building. The analysis of the global thermal behavior of the winery shows that the temperature inside follows the trend outside throughout the year, without significant differences in the annual or monthly average. This is a consequence of the fact that the constructive design gives priority to ventilation to ensure a correct development of the "veil of flor". In contrast to the behavior of red wine cellars described in previous works (Mazarrón et al., 2012), the construction is ineffective in damping monthly temperature variations.

However, there are notable variations in temperature throughout each day. Daily temperature damping (difference between the outside and inside daily temperature range, expressed as a percentage of the outside) is greater than 50% throughout the year, which translates into indoor temperatures up to 9 °C lower at the hottest hours. The particular design of the winery and its large volume is effective in buffering the abrupt temperature variations from the outside. Given the different response to hourly and daily variations, it is necessary to perform a validation of the model at both the daily and hourly scales.

Additionally, there is a strong phenomenon of vertical stratification of temperature (Navia-Osorio et al., 2022), with an annual mean value of 2.3 °C (0.21 °C/m). This phenomenon is especially pronounced in the summer months, during the hours of greatest sunshine, with differences that exceed 5 °C between the lower and upper part of the cellar. It is important to understand this phenomenon, as it implies substantial differences in temperature between the ageing zone and average of sensors considering the

237 whole height of the winery (up to 11m). Therefore, stratification must be taken into account when  
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238 analyzing the results. On the contrary, the horizontal uniformity analysis showed that the thermal  
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239 behavior in the four locations was practically identical throughout the year, with a maximum variation of  
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240 0.6 °C in the warmest month.  
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### 3.2 Validation of the simulation model

The energy simulation model obtained from the two full monitored years using DesignBuilder® has been validated based on the recommendations proposed by FEMP (Webster et al., 2015) and ASHRAE (2014). The values of NMBE, CV and R<sup>2</sup> have been obtained for the daily and hourly results (Table 2).

Table 2: Validation indices of the developed model calculated with monitored data. Daily scale (left) and hourly scale (right)

Regarding the daily behavior, the model reproduces the evolution of temperatures with great accuracy. In this way, the daily coefficient of determination obtained is 99% in the two years analyzed. Taking into account that the minimum recommended threshold value is 75%, it can be affirmed that the model is valid to reproduce the annual evolution over the year. As a graphic example, Figure 7 shows the average daily temperature inside the winery compared to the result obtained by simulation.

Figure 7. Trend of the mean daily temperature (measured and simulated) inside the winery throughout the year.

Regarding the hourly behavior, the model also reproduces with high accuracy the temperature variations throughout each day, despite the strong ventilation in the cellar. As an example, Figure 8 shows the daily temperature evolution of the hottest and coldest weeks of one year. The model has an hourly coefficient of determination of 97%. As in the previous case, taking into account that the recommended minimum is 75%, it can be stated that the model is valid on an hourly scale.

Figure 8. Hourly trend of temperature (measured and simulated) in the hottest week (up) and the coldest week (down).

261 The comparison of the outdoor temperature data monitored with historical series from the nearby  
1 climatological observatory demonstrates the representativeness of the years used for validation (Figure  
262 9). Most of the year, the monitored values are within the range of the historical series. The average  
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266 Figure 9. Representative values of the historical series from 2004 to 2011 versus the two monitored years of outdoor  
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18 **3.3 Climate Change weather data**  
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270 Nine EPW data files (that include the historical series and the two years monitored) were transformed  
271 using “CCWorldWeatherGen”, according to the HadCM3 predictions, for the time periods 2050 (CC2050)  
272 and 2080 (CC2080) (Figure 10). For the CC2050 scenario, considering the average of the historical series,  
273 an increase in the annual mean temperature of 2.3 °C is observed, with an increase in the maximum  
274 temperature of 3.6 °C in summer. Considering the maximum values of the historical series, the  
275 temperature could increase more than 4 °C in the summer of hot years.

280 Figure 10. Effect of climate change on outdoor temperature (mean daily) according to HadCM3 prediction for 2050 and 2080  
281 (CCWorldWeatherGen).  
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283 In this sense, it should be noted that other authors obtain similar predictions for their studies in  
284 different regions of Spain. Thus, Ribalaygua et al. (2013) analyzed four climate models under different  
285 future emission scenarios over the Spanish region of Aragón and predicted, for the middle of the  
286 century, an increase in the average temperature of between 1.5 and 2.5 °C. Portero et al. (2020)  
287 analyzed 14 different regionalized dynamic climate projections and predicted an increase of more than 5

287 °C, by the end of the 21st century, in southwestern Spain. Therefore, the average temperature  
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288 prediction made by the CCWorldWeatherGen tool appears to be supported by other scientific work in  
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289 the study area.  
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290 The climatological files (epw) not only predicts the average temperature increase, but also allows to  
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291 simulate hourly and daily temperature variations based on those occurring today. This aspect is  
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292 fundamental when correctly estimating the effect of climate change in Sherry wineries, due to the large  
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293 variations previously described as a consequence of ventilation. Without reproducing these  
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294 temperature changes, the results would be incomplete. This is not the case in red wine cellars, where  
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295 stability is much more pronounced: daily variations can reach an average value of 0.1 °C /day (Mazarrón  
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296 et al., 2012).  
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### 3.4 Analysis of thermal comfort

#### a) Current situation

300 From the monitoring data, it is verified that the average temperature of the ageing zone is within the  
301 comfort zone established in 93% of the values measured every 15 minutes. Abrupt temperature changes  
302 due to ventilation cause the limits described in the literature to be exceeded. However, these excesses  
303 are usually very short-lived, so they should not affect the temperature of the veil. Considering daily  
304 average values, the temperature exceeds the comfort limit on 4% of the period, although on most days  
305 only by a few tenths of a degree. Considering the thermal inertia of the wine and the insulation of the  
306 barrel, the wine should be within the comfort range most of the year. Therefore, in the absence of  
307 climate change, the production of sherry wine would not be endangered, since the temperature remains  
308 within the limits for the survival of the “veil of flor” described in the specialized literature.  
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311 The temperature in the ageing area obtained by simulation with DesignBuilder using the historical series  
312 of outdoor temperature corroborates the behavior described. The average temperature of the nine

311 years remains within the comfort zone throughout the year (Figure 11). Only the limits are slightly  
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312 exceeded in years of more extreme temperatures (maximum and minimum values of the 9 years).

313 Figure 11. Effect of climate change on the temperature in the ageing zone, according to the HadCM3 prediction for 2050 and  
314 2080 (CCWorldWeatherGen).

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1216 b) 2050 and 2080 prediction

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1517 The energy simulation program (EnergyPlus) assumes the total space of the simulation area in a  
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318 simplified way. However, as explained above, there is a substantial difference between the average  
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2019 temperature of the cellar and the temperature of the ageing zone, due to the stratification  
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2220 phenomenon. In this sense, for the simulation results of the scenarios CC2050, CC2080 and present  
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321 situation, the mean temperature values of the ageing zone have been estimated by interpolating the  
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2722 percentage variation of the stratification, obtained from experimental data.

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3123 Using the validated model, the simulation of climate change scenarios was carried out using nine  
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3324 transformed climatological files from the historical series for 2050 and another nine for 2080. For the  
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3525 CC2050 scenario, considering the average of the historical series, the model predicts that 19% of the  
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3726 mean values will be outside the comfort zone, or what is the same, the winery will be outside the  
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4027 comfort zone for a period of 68 days (Figure 11). This period would increase to 124 days considering the  
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4228 extreme values of the historical series. For the CC2080 scenario, the mean values will be outside the  
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329 comfort zone 27% (98 days). If the threshold values for “veil of flor” survival described in the literature  
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46  
4730 are correct, so many days of excess temperature would eventually affect the veil and lead to its death.  
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4931 This would happen almost continuously during the summer period (Figure 11).

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5232 Moreover, during spring and autumn, when yeast activity is at its peak (Domecq, 2011), the mean  
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5533 temperature will increase by 1.4 °C and 1.0 °C respectively for the CC2050 scenario. During these  
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5734 seasons, the increase will reach 2.9 °C and 2.2 °C for the CC2080 scenario. Therefore, yeast development  
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335 would also be significantly affected.

336 If the climate change estimates presented in this work are confirmed in the future, companies will have  
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337 difficulties maintaining the comfort temperature inside the warehouse while maintaining high natural  
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338 ventilation. The conditioning of a large flow of outside air would entail a very high energy cost, which  
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339 could affect the competitiveness and viability of the sector. The introduction of changes in construction  
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340 design or the incorporation of environmental control technologies will be key aspects to be analyzed in  
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341 the near future.

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#### 17 **4 Conclusions**

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344 The research carried out analyzes for the first time the impact that climate change will have on the  
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345 biological ageing of Sherry wine. The importance of the results provided in this study should be  
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346 highlighted due to the great sensitivity of the yeasts involved in the “veil of flor” to high temperatures  
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347 and the risk of collapse of the process and the economic engine of the area. Currently, the biological  
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348 ageing of Sherry wine is an example of a sustainable process thanks to the “Cathedral warehouses”,  
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349 which are a good example of NZEB. It’s simple but effective construction strategies allow to maintain a  
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350 thermal comfort necessary for biological ageing, even with constant ventilation needs. These buildings  
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351 can achieve temperature reductions of up to 9 °C in the hottest hours without any type of cooling  
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352 systems, thanks to the thermal phenomena of damping and stratification.

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353 A new simulation model for these types of buildings has been developed and validated using  
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354 DesignBuilder® software. This model allows us to estimate the effect of climate change on its  
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355 performance and effectiveness.

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356 If the global warming forecasts are fulfilled, by 2050 the average temperature in the south of Spain  
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357 could increase by 2.3 °C. In this scenario, these buildings are not prepared to absorb these increases in  
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358 temperature. As the model shows, the winery under study would exceed the comfort limits for 19% of  
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359 the year (average of the nine years historical series). As a result, the yeasts could not maintain their  
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360 activity for a long period, affecting the characteristics and quality of the wine. The urgent need of the

361 Sherry wine sector to implement new strategies and adapt buildings to the changes that will occur in the  
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362 coming decades is clear. However, the difficult economic situation that it has been going through in  
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363 recent decades, immersed in a restructuring process, has aggravated its situation. The developed  
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364 simulation model should be a useful tool for evaluating adaptation measures and new potential  
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365 locations.

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366 But the Sherry wine industry is not the only victim of this fatal change. The industrial activities carried  
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367 out in Near Zero Energy Buildings will need to be updated to the new context in the coming decades if  
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368 they wish to continue maintaining a sustainable production model. In this sense, there is a need in the  
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19  
369 research world to develop new works in this line that anticipate solutions for the inevitable future  
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370 context.

## 372 Acknowledgments

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373 This study has been carried out as part of the BIA2014-54291-R research project, funded by the Spanish  
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374 Ministry of Science and Innovation.

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**Declaration of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Ignacio Canas reports financial support was provided by Spain Ministry of Science and Innovation.

## **Highlights**

Assess the impact of climate change in a Near Zero Energy Building

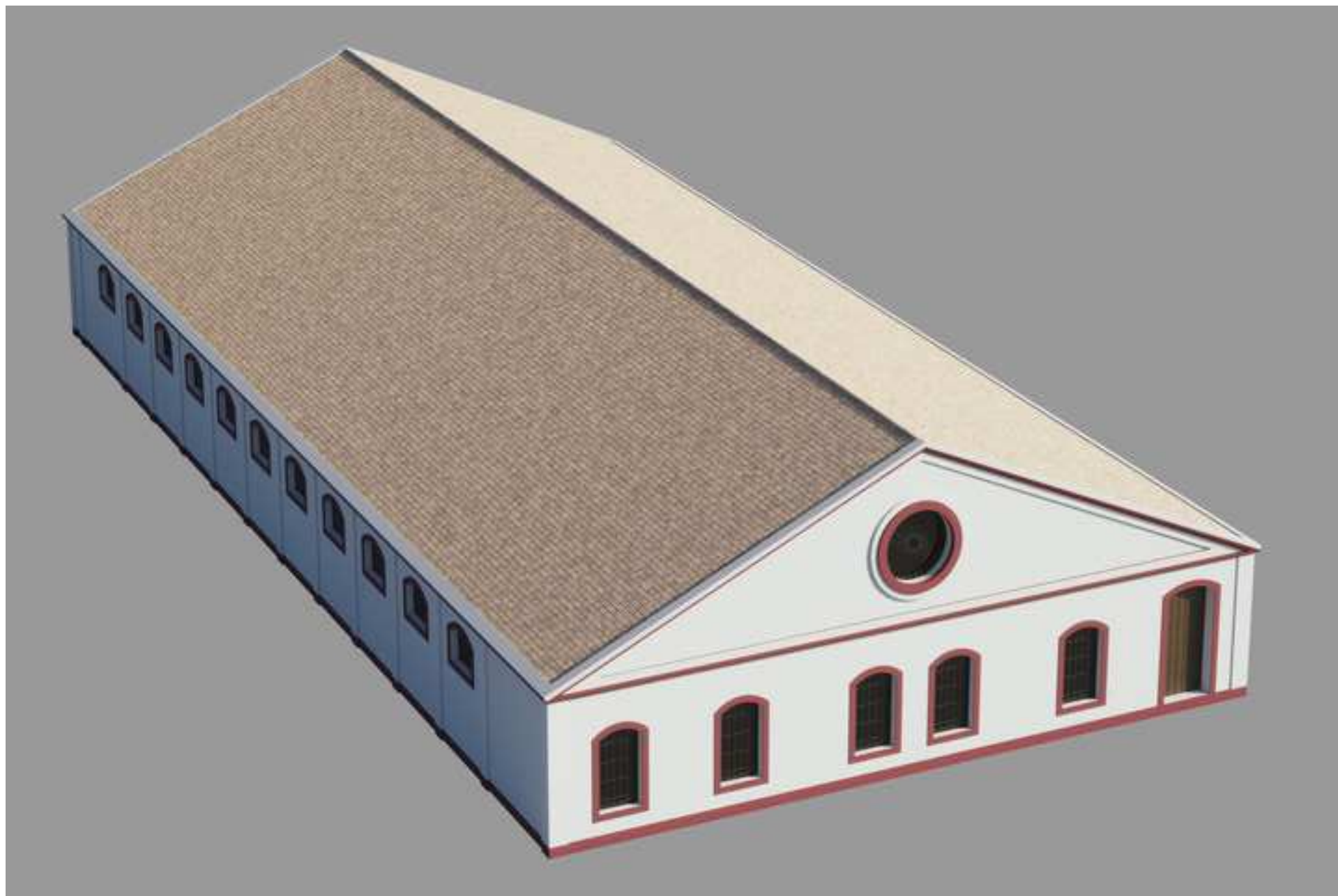
“Cathedral warehouses” will lose their usefulness by the middle of this century

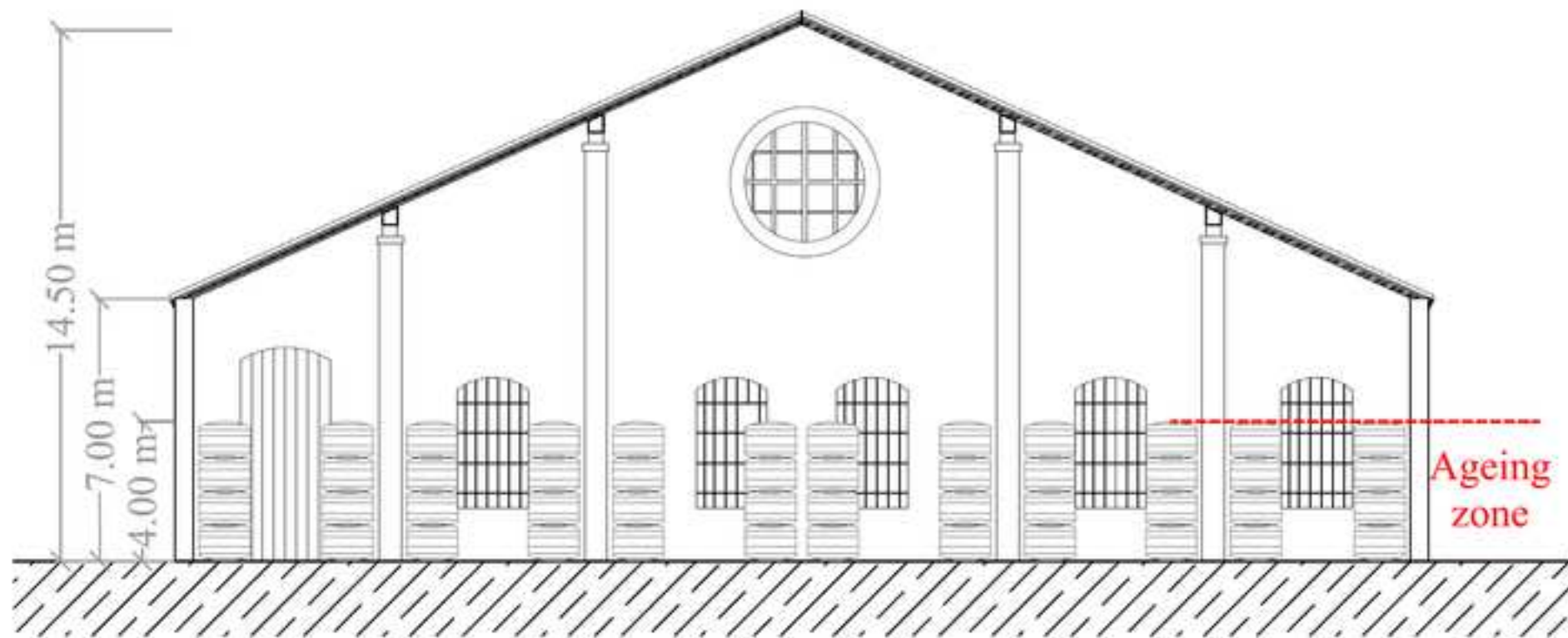
Comfort limits will be exceeded 19% of the year, interrupting biological ageing

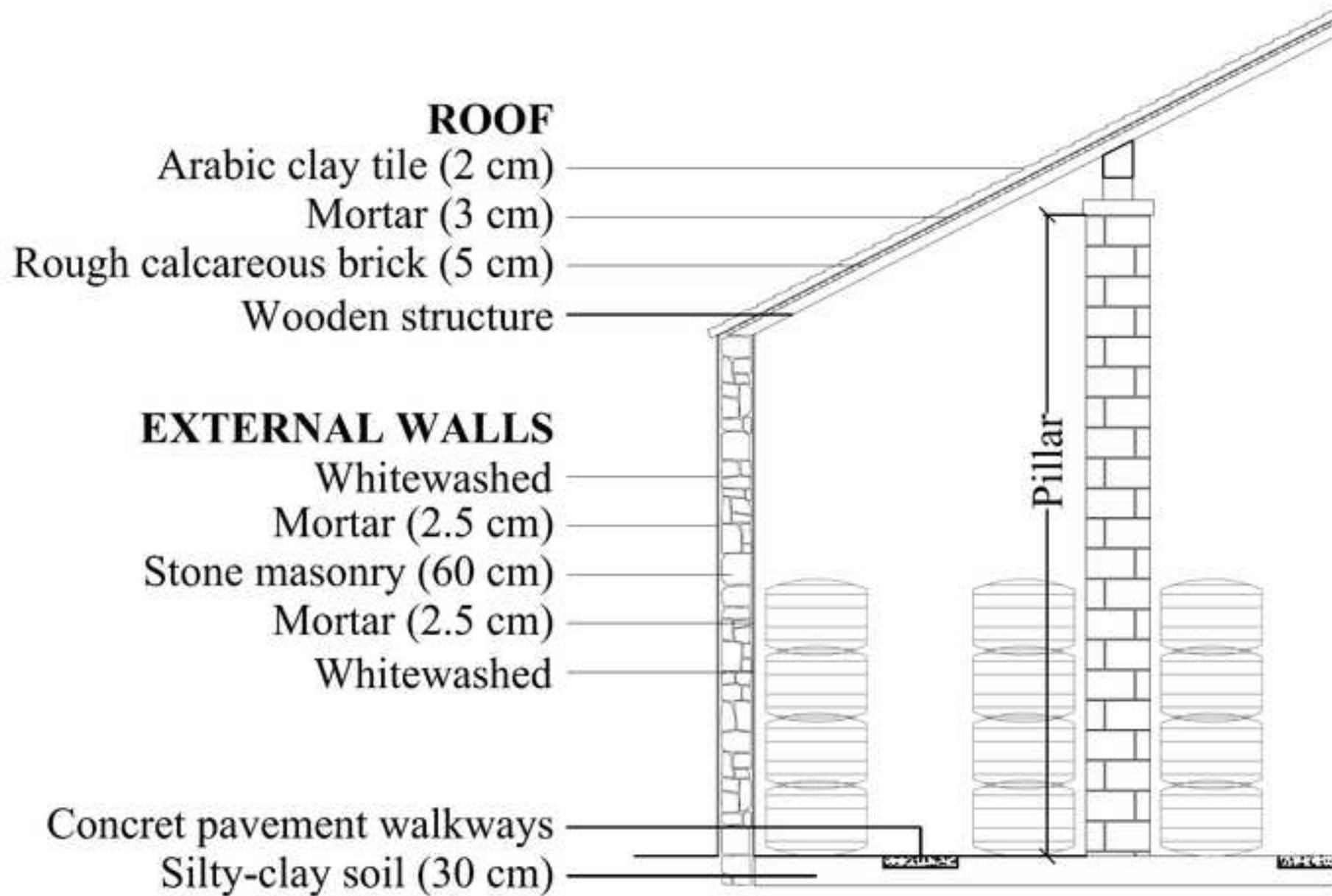
The economic sustainability of an entire region would be endangered

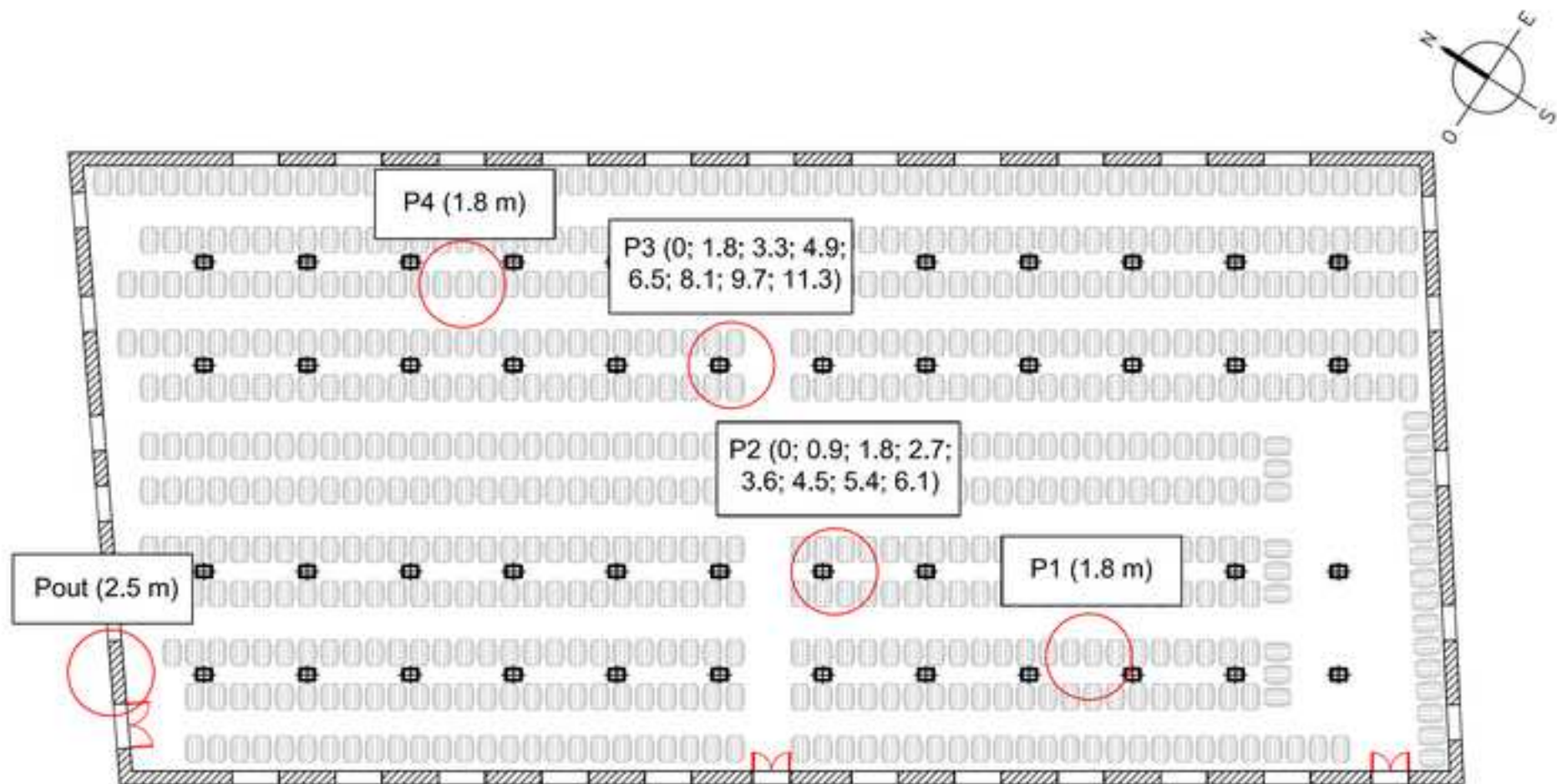
The need to evaluate the future behavior of Near Zero Energy Building is highlighted

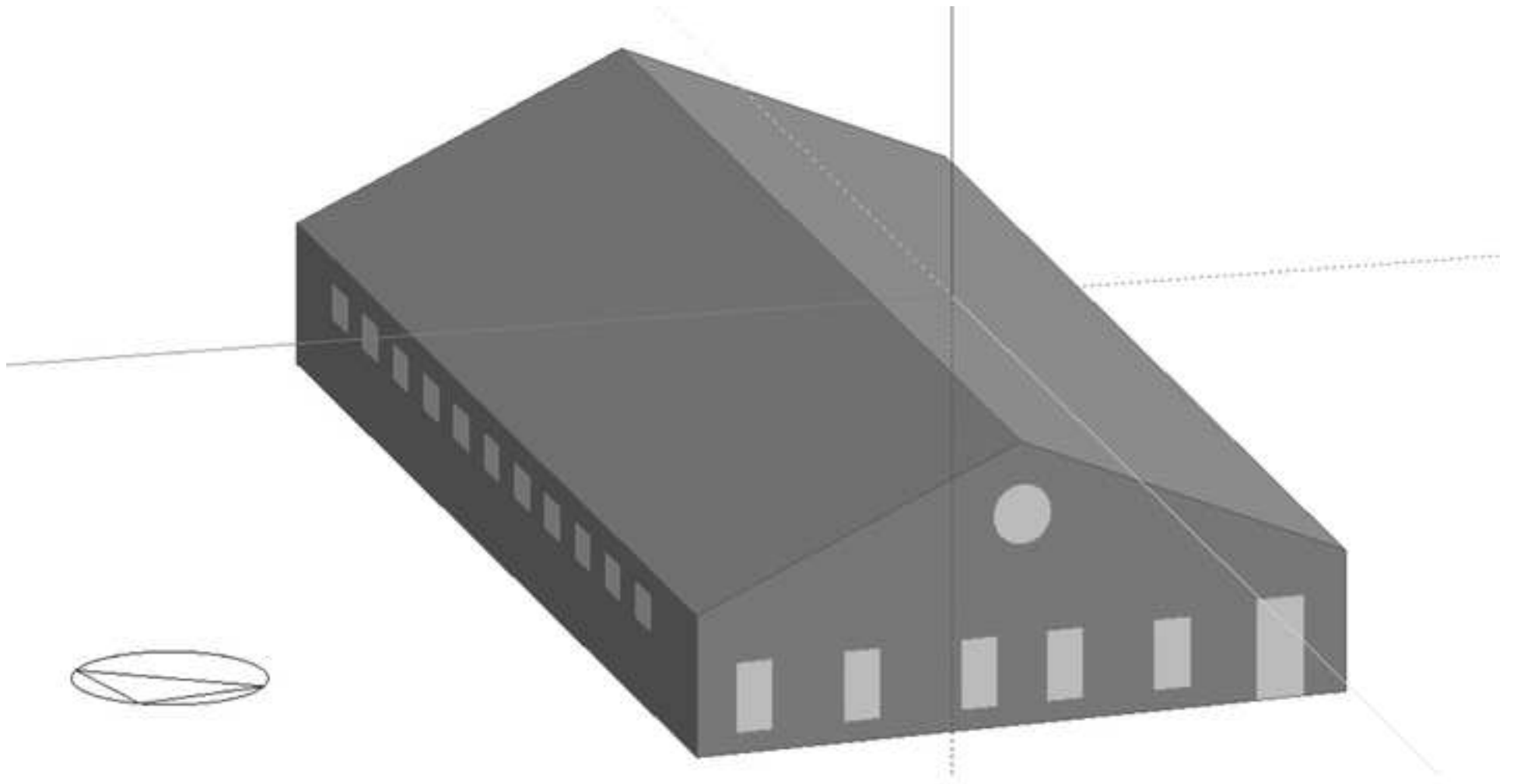


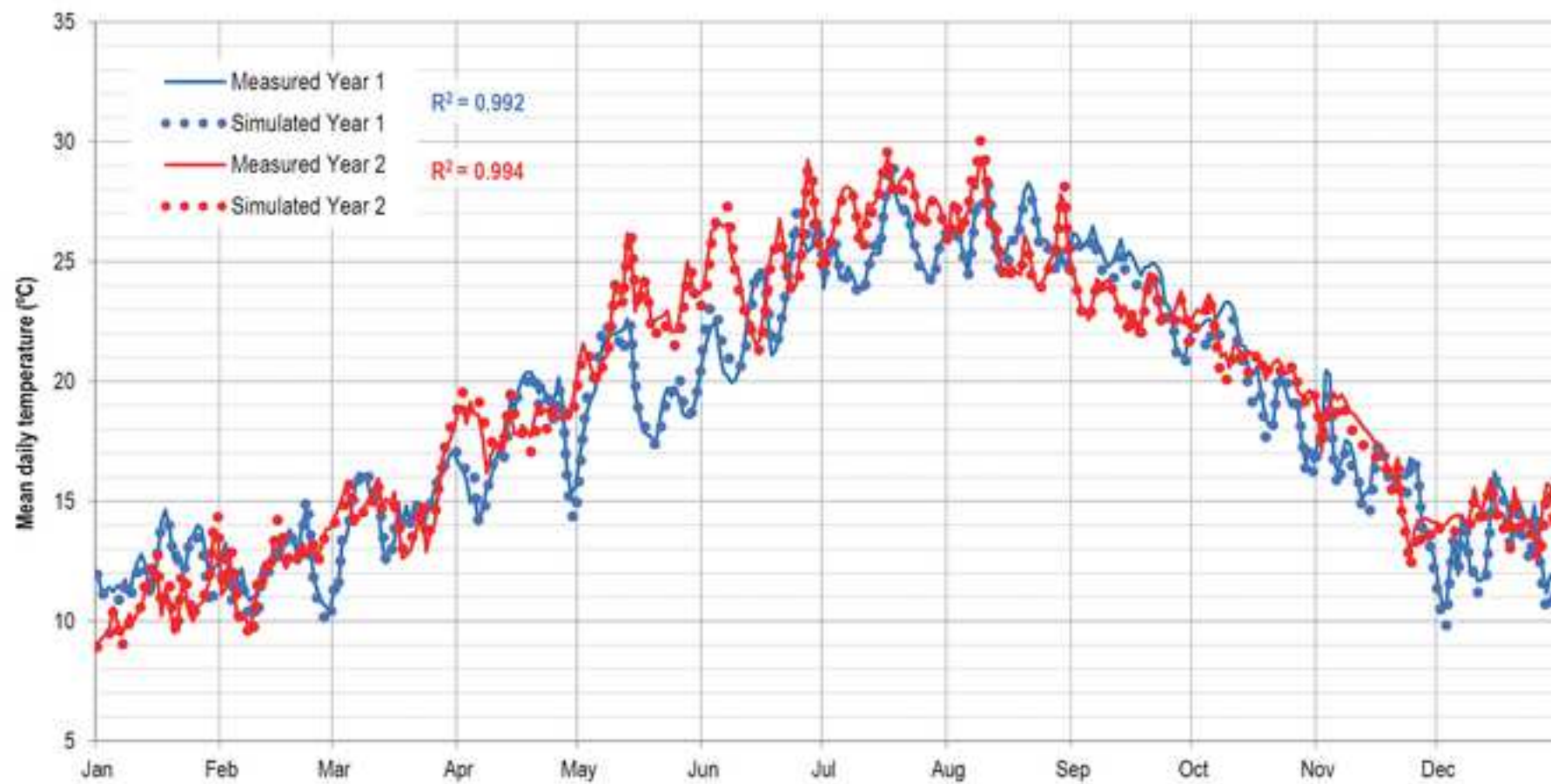


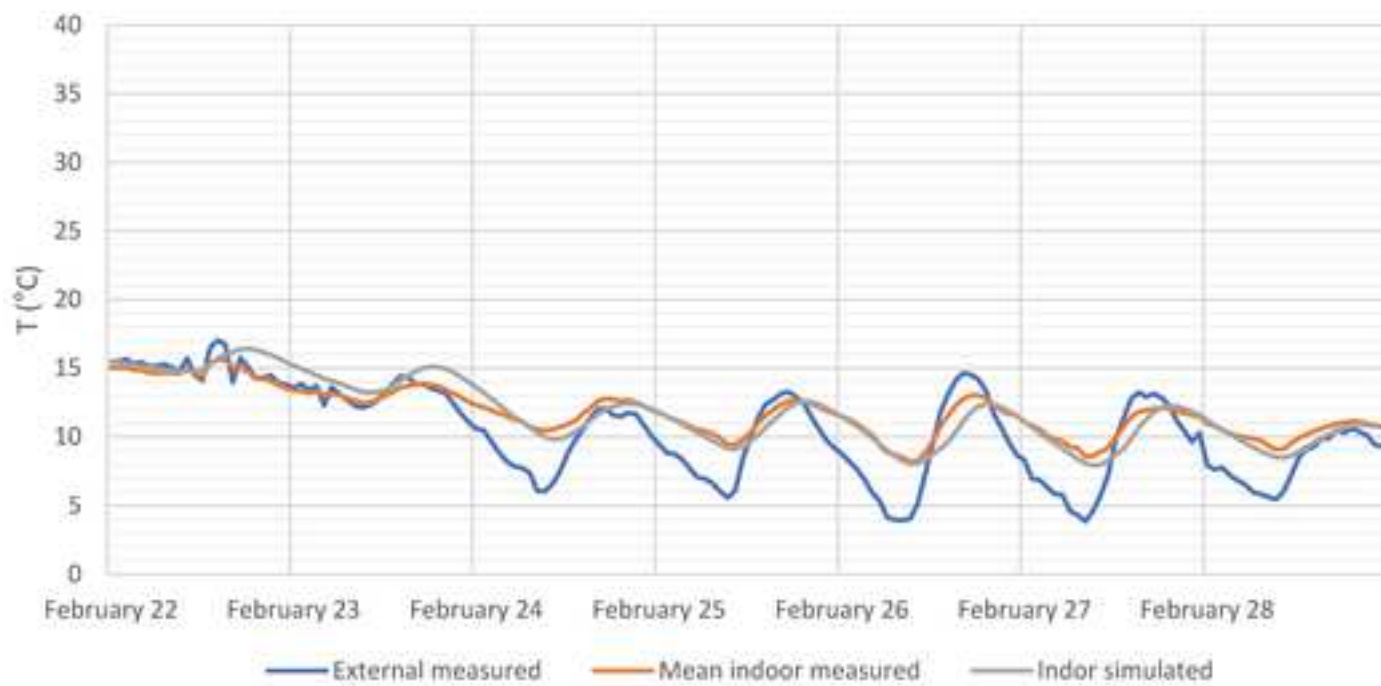
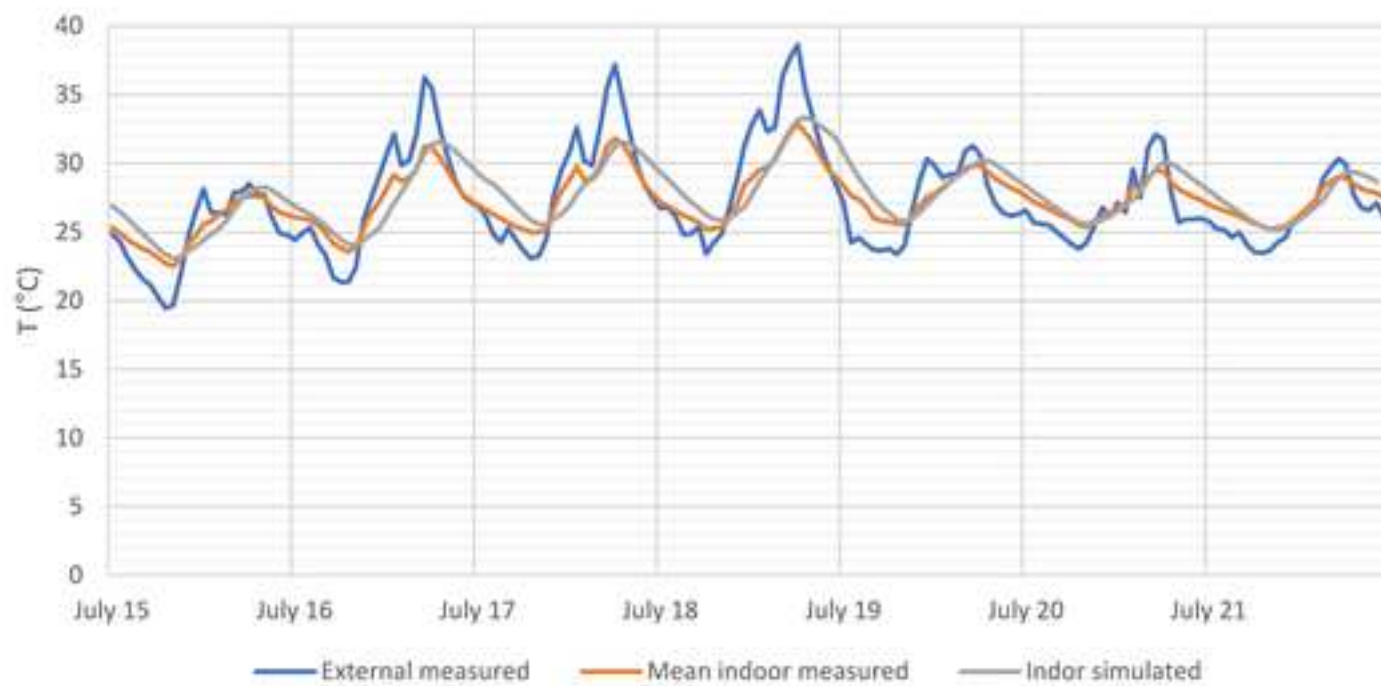


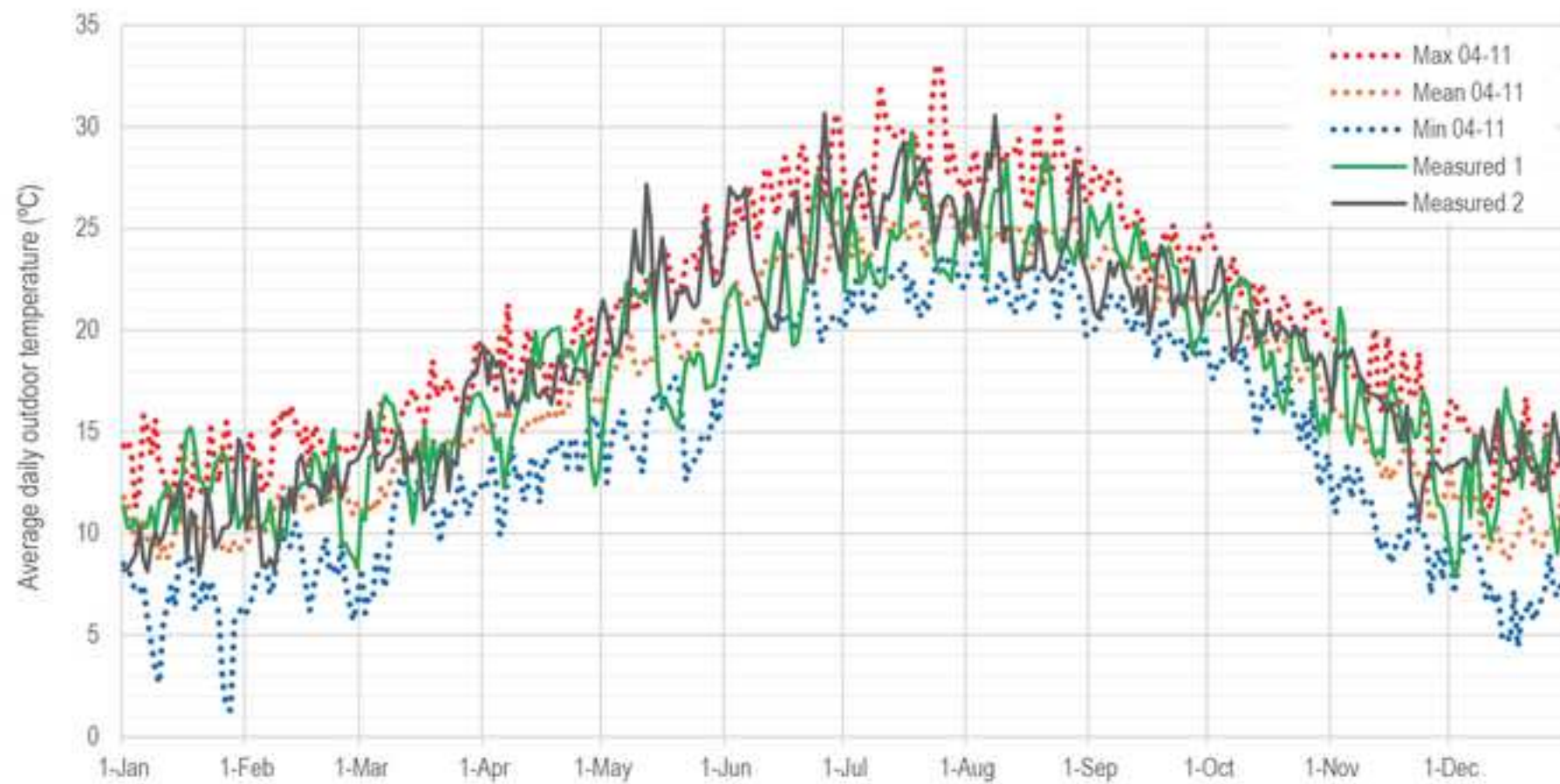


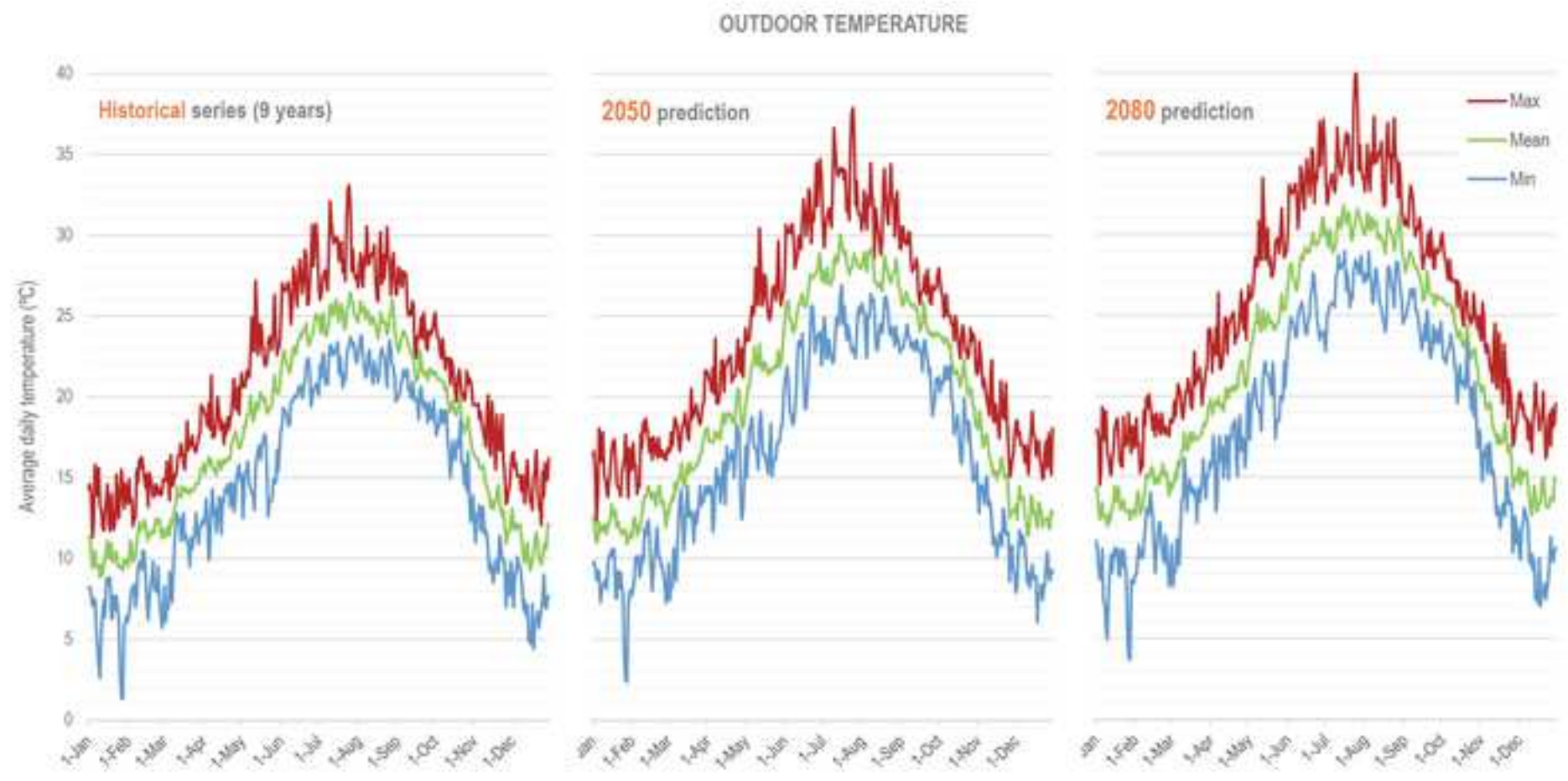












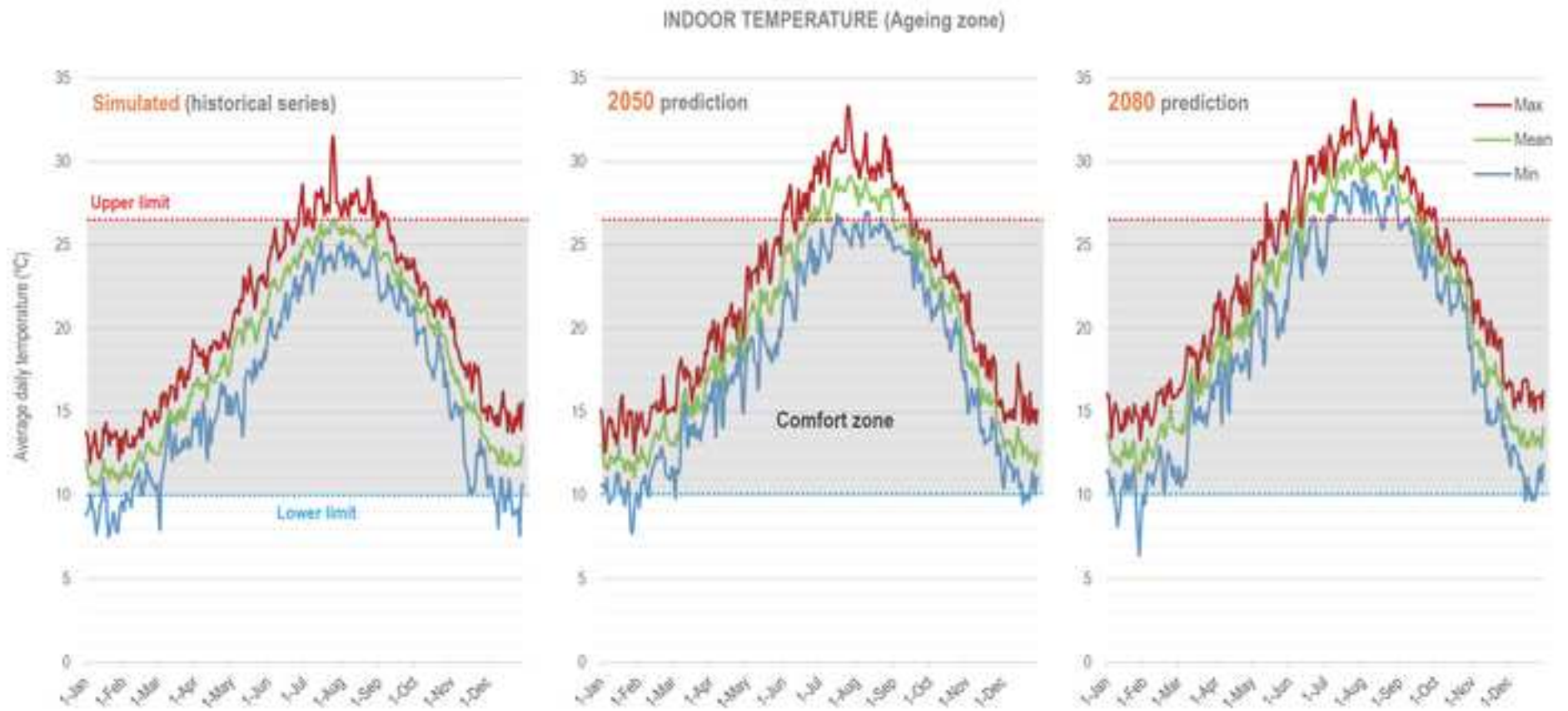


Table 1: Thermal values of the enclosures used in the proposed model.

	<i>e</i>	<i>ρ</i>	<i>Cp</i>	<i>μ</i>	<i>λ</i>	<i>R</i>
<b>External walls</b>						
Mortar	0.025	2100	1000	10	1.3	0.019
Masonry (Ostionera stone)	0.600	2050	1000	250	0.55	1.091
Mortar	0.025	2100	1000	10	1.3	0.019
Internal Surface resistance						0.13
External Surface resistance						0.04
					<b><i>ΣR</i></b>	<b>1.30</b>
					<b><i>U</i></b>	<b>0.77</b>
<b>Pitched roof</b>						
Arabic tile (baked clay)	0.020	2000	800	30	1.00	0.020
Mortar	0.030	2100	1000	10	1.3	0.023
Rough calcareous brick	0.050	2300	1000	10	0.85	0.059
Internal Surface resistance						0.10
External Surface resistance						0.04
					<b><i>ΣR</i></b>	<b>0.24</b>
					<b><i>U</i></b>	<b>4.13</b>

Where: *e* = thickness (m); *ρ* = Density (kg/m<sup>3</sup>); *Cp* = Specific heat capacity (J/kg·K); *μ* = Water vapor diffusion resistance factor (dimensionless); *λ* = Conductivity (W/m·K); *R* = Thermal resistance (m<sup>2</sup>·K/W); *U* = Thermal transmittance (W/m<sup>2</sup>·K).

Table 2: Validation indices of the developed model calculated with monitored data. Daily scale (left) and hourly scale (right).

<i>Index</i>	<i>Daily scale</i>			<i>Hourly scale</i>		
	<i>Year 1</i>	<i>Year 2</i>	<i>Tolerance</i>	<i>Year 1</i>	<i>Year 2</i>	<i>Tolerance</i>
<b>NMBE</b>	1.02 %	0.75 %	±5%	1.02 %	0.75 %	±10%
<b>CV (RMSE)</b>	2.77 %	2.41 %	±5%	5.44 %	5.08 %	±30%
<b>R<sup>2</sup></b>	99.16 %	99.36 %	>75%	96.57 %	97.07 %	>75%

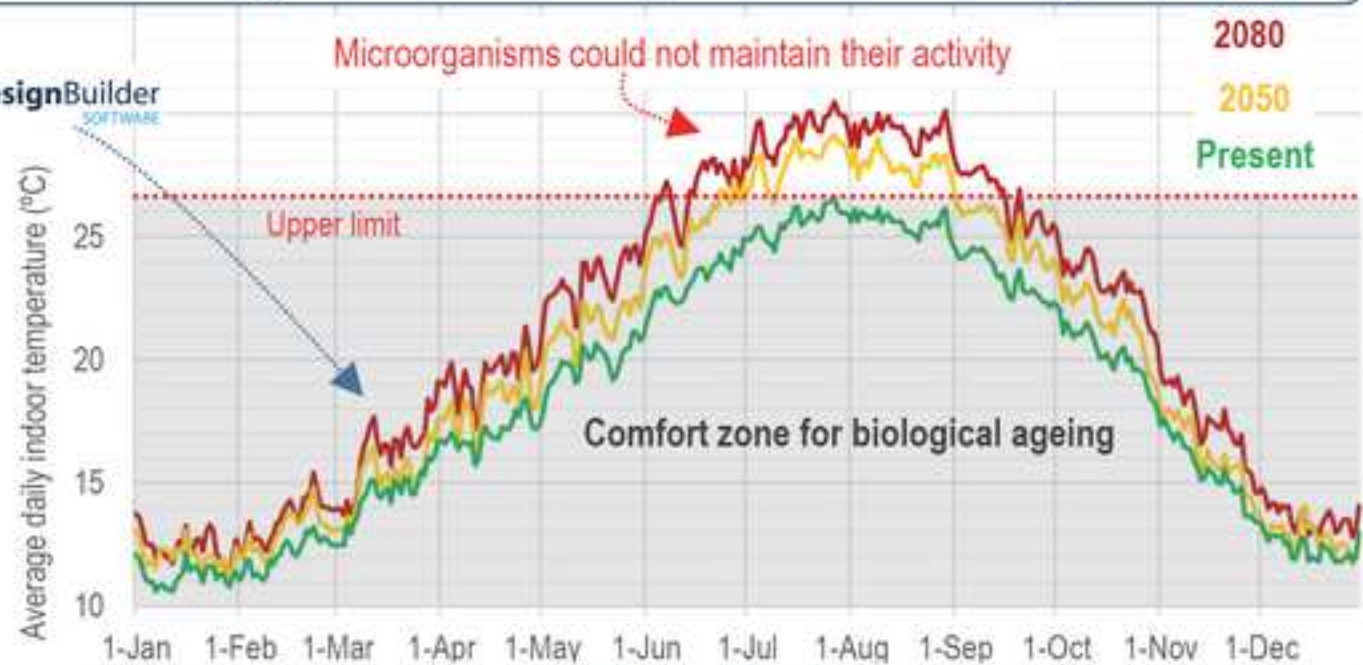
## Impact of climate change on sustainable production of Sherry wine



DesignBuilder  
SOFTWARE



Navia-Osorio, Porras-Amores,  
Mazarrón, Cañas (2022)



**CONCLUSION:** The "Cathedral warehouses", example of Nearly-Zero Energy Buildings, are not prepared for the effect of climate change. The indoor temperature would exceed the limits for the development of the biological ageing. The microorganisms responsible for this unique process could not maintain their activity.

## **Author Contribution**

Eduardo Galán: Conceptualization, Software, Validation, Writing - Original Draft, Visualization, Writing - Review & Editing.

Cesar Porras-Amores: Conceptualization, Investigation, Software, Validation, Writing - Review & Editing.

Fernando R. Mazarrón: Conceptualization, Methodology, Formal analysis, Data Curation, Writing - Review & Editing.

Ignacio Cañas: Conceptualization, Supervision, Project administration, Funding acquisition.