A4.3.2: STATE OF THE ART ANALYSIS ON BUILDING PERFORMANCE SIMULATION ON HISTORIC BUILDINGS

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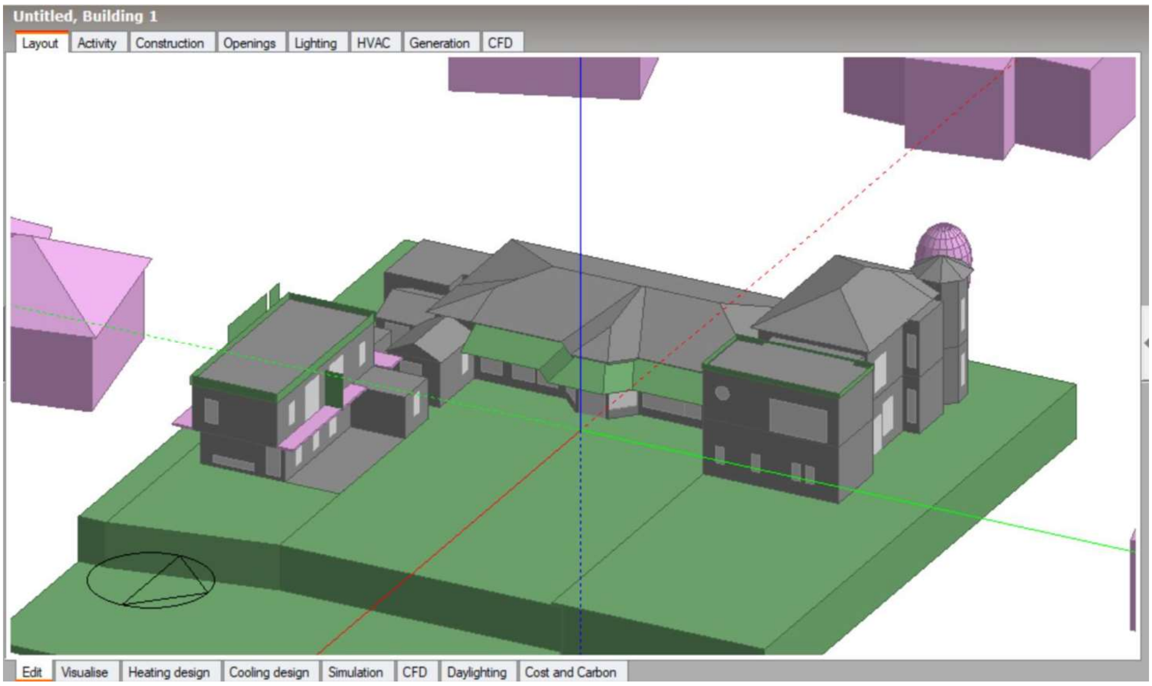
Abstract

This document is part of the Activity 4.3.2: “State of the Art analysis on Building Performance Simulation on historic buildings”. The purpose of this document is to introduce the reader to the advantages of applying Building Performance Simulation (BPS) methodologies and tools on built heritage, in Section 2. BPS allows the study and optimisation of energy performance in an interrelated way, through the creation of a behavioural model of a given historical urban fabric, building or wall element. The purpose of simulations is not only to reveal the interactions between the building, occupants, HVAC systems and the outdoor climate, but also to facilitate the use of environmentally and energy-efficient design solutions, in order to acquire relatively rapid feedback on the performance implications of the design hypotheses. The document aims to provide important information from the literature about the current challenges regarding the employment of BPS in historic buildings, in order to allow the Project partners to better understand how the energy modelling tools can be used in the case of built heritage renovation and/or retrofit activities, in Section 3; the state-of-the-art in model calibration approaches, in Section 4, because, as models always represent a simplification of real cases, the reliability of predictions provided by simulation models requires a thorough calibration process. The document concludes in Section 5, with a brief description of the compromises and a list of points that need to be addressed when applying a simulation-based design approach to a historic building, including issues of material performance uncertainties, simplifications imposed to the modelling and simulation by software limitations, building material as well as occupant behaviour anomalies/unpredictability, and other points.



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1 INTRODUCTION

Building Performance Simulation (BPS[1]) allows the study and optimisation of energy performance in an interrelated way, through the creation of a behavioural model of a given historical urban fabric, building or wall element, reduced to a certain level of abstraction (Augenbroe 2002). The main innovation introduced by the simulations, with respect to previous methodologies of analysis and evaluation of the energy-environmental performance of buildings, is the possibility of treating them as an integrated system of related elements that can be optimized and not as the sum of elements designed and optimised separately (Hensen 2004). The purpose of simulations is not only to reveal the interactions between the building, occupants, HVAC systems and the outdoor climate, but also to facilitate the use of environmentally and energy-efficient design solutions (Hong, Chou, and Bong 2000). The simulations, in fact, support users in understanding complex phenomena by providing relatively rapid feedback on the performance implications of the design hypotheses (Clarke and Hensen 2015). Yet, the application of these tools on historic buildings is still in an experimental phase and subject to certain challenges. In this document, various cases of this integration will be presented in order to exploit and implement their findings within the BEEP approach.

2 ADVANTAGES OF USING BUILDING PERFORMANCE SIMULATION ON THE BUILT HERITAGE

In the field of historical built heritage, building performance simulation are particularly interesting because they guarantee innovative non-destructive applications in both pre-diagnostic and diagnostic terms (E. Gigliarelli et al. 2017). These tools in fact:

- facilitate the understanding and analysis of complex phenomena, dynamically studying the exchange of energy between the building and the surrounding environment including biophysical (water, soil, vegetation) and bioclimatic (solar radiation and ventilation) factors. This allows for innovative applications also in non-destructive analysis techniques;
- provide retroactive feedback on the evolution of decay phenomena and on energy and environmental implications of conservation interventions. We refer to specific heat, air and moisture transport software for predictive analysis in building envelopes, or to the possibility of dynamically studying the trend of physical quantities related to comfort (but also to the possible formation of degradation phenomena) within each single room;
- allow, through the methods of environmental analysis, to investigate the constructive events of ancient architecture in ways so far completely unexplored, that are halfway between virtual and experimental archaeology, reconstructing models to be studied (e.g. allowing to study how the spaces were probably used in a building or how back in the day devices were used to improve comfort of occupants, provide further elements to a historical analysis).

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[1] Also referred to as Building Energy Modelling – BEM, Building Energy Simulation –BES.

Moreover, the simulation-based study of the bioclimatic behaviour of historic fabrics provides an added knowledge value to the explorative process of the building itself, allowing the possibility to model its natural functioning processes, paving the way for design solutions capable of enhancing its distinctive characteristics and identities linked to the local microclimate (GBC 2017; E. Gigliarelli, Calcerano, and Cessari 2016).

3 ENERGY MODELLING TOOLS USED IN THE CASE OF HISTORIC BUILDINGS

Currently, several simulation software are available for the evaluation of energy performance of buildings. These tools can be classified as static, semi-dynamic and dynamic. Stationary and semi-dynamic approaches are simplified methods that consider a limited number of factors. They are more related to the evaluation of energy performance in standard conditions of use and usually input data are provided by standard references from national databases, used for energy labelling. In particular, results from static tools are simplified as they do not consider the periodic trend of temperature and do not take into consideration thermal inertia of the structures. Semi dynamic software (also called sketch design software) take this parameter under consideration, yet they require simplified inputs for climatic data and building description. On the contrary, dynamic simulation software are able to evaluate accurately all factors but they need detailed input data for climatic conditions and building properties.

Calzolari (2016) studied the criticalities of applying BPS, generally used for new or existing buildings, to the built heritage. Pracchi (2014) and Heath et al. (2010) each simulated a historic building using multiple BPS software programs and found large discrepancies between results from the different programs, illustrating the ways in which these limitations (§ Chapter 5) can have downstream effects on retrofit decision-making. Despite the complexity of whole building, i.e. dynamic software tools, they are acknowledged as more suitable for the modelling of historic buildings due to their flexibility and capacity to produce more accurate results (Adhikari et al. 2013).

Simulation software is extremely useful in calculating environmental conditions and energy consumption in buildings prior to intervention, as it allows the behaviour of the different climate conditioning systems and installations to be predicted (Webb 2017). The capacity of numerical tools to minimise the computational time for evaluating finite set of alternatives based on various criteria is extremely valuable for the development of multiple criteria decision analysis tools. The project Climate for Culture has coupled climate modelling with whole building simulation tools. The project scope was to provide information on future indoor climate change and address the risks for cultural heritage. Various online tools were produced, as well as a Decision Making Support System providing general information for stakeholders. Similar tools were also developed through several projects focusing on retrofitting historic buildings, such as SECHURBA[2] (AA. VV. 2011; E. Gigliarelli, Calcerano, and Cessari 2018) and EFFESUS[3].

A thorough review of studies regarding historic buildings employing numerical tools (CFD[4] or BPS) is provided in the work of Martínez-Molina et al. (2016). The studies are grouped per building use and method of analysis (i.e. monitoring, simulation, CFD, etc.). In the case of museums, libraries and theatres, most of the studies focus on the regulation of the microclimatic environment; an important aspect in order to minimize the ageing and degradation of the materials and artworks (Muñoz-González et al. 2018). Tronchin and Fabbri (2017) used Building Performance Simulation to optimise energy consumption and ancient manuscripts conservation in the Malatestiana Library in Cesena (Italy). A methodology for microclimatic qualification assessment is described in the study of Corgnati, Fabi, and Filippi (2009), which is based on medium/long field monitoring of environmental parameters and a microclimatic quality evaluation in museums. Silva, Coelho, and Henriques (2020) discussed the indoor microclimatic monitoring of a church in Lisbon (Portugal) and compared the results with other case studies in different European geographical areas, to propose a new method of analysis specifically dedicated to temperate climates (Silva and Henriques 2014). The work of Camuffo et al. (2010), Schellen and Neuhaus (2010), Muñoz González et al. (2020), Varas-Muriel, Martínez-Garrido, and Fort (2014) focus on simulating active environmental conditioning systems such as heating, ventilation, air-conditioning and cooling (HVAC) in churches. In the recent work of de Rubeis et al. (2020), an extensive review of similar studies is provided, reporting the results of reseaches employing air-to-air heat pumps, adaptive ventilation (Napp and Kalamees 2015) or variable heating and cooling setpoints (H. L. Schellen and van Schijndel 2011).

Different indoor conditions, such as natural lighting, were analysed in other studies employing whole building simulation tools. Balocco and Calzolari (2008) performed a natural lighting design research in a medieval church in Florence, Italy. A solar radiation control showed that the installations ensured energy savings for cooling and lighting and as well as guaranteeing users' lighting comfort. Michael et al. (2017) coupled natural lighting field measurements with numerical simulations in vernacular buildings in Cyprus in order to assess lighting comfort. Nocera et al. (2018) developed a calibrated model based on the Radiance software to improve daylight performance in a classroom of the Caserma Gaetano Abela in Sicily (Italy).

Additional analysis and uses of numerical tools concern the estimation of air quality and the use of innovative materials. Cataldo et al. (2005) studied air quality in a cultural heritage building by integrating different non-destructive methods, such as microclimatic and ground penetrating radars. Bernardi et al. (2014) showed the efficacy of phase change materials when used as thermal energy storage units in heritage buildings. The study revealed, that direct contact between phase change materials and heritage objects is not recommended, as mechanical damage could result.

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[2] SECHURBA Research Project: Sustainable Energy Communities in Historic Urban Areas'. 2011 https://ec.europa.eu/energy/intelligent/projects/en/projects/sechurba

[3] EFFESUS Research Project: Energy Efficiency for EU Historic Districts' Sustainability'. 2016 https://www.effesus.eu/

[4] Computational fluid dynamics, another branch of numerical analyses, addressed later in the paragraph.

A numerical tool used for predicting indoor and outdoor airflow, heat transfer and indoor thermal comfort, that is gaining ground over the last decades, is Computational Fluid Dynamics (CFD). There are a few applications of CFD in the sector of building conservation. Balocco and Grazzini (2009) investigated the ancient natural ventilation system inside a historical building in Palermo, Italy, and analysed a simple cooling technique. Papakonstantinou, Kiranoudis, and Markatos (2000) modelled thermal comfort conditions in the Hall of the National Archaeological Museum of Athens, while D'Agostino and Congedo (2014) investigated the adequacy of natural ventilation in a historical building located in the South of Italy. The model determined a great variability of the thermo-hygrometric parameters among the ventilation solutions. Kristianto, Utama, and Fathoni (2014) investigated the thermal comfort conditions in the Minahasa Traditional House, suggesting greater silts height and roof openings for enhanced airflow in indoor spaces. Finally, Du, Bokel, and van den Dobbelsteen (2014) coupled field measurements and dynamic thermal and CFD simulation through the platform of Design Builder in order to investigate the thermal performance of the vernacular Chinese house.

Pisello et al. (2014) used BPS to support the energy refurbishment of Palazzo Gallenga Stuart in Perugia (Italy) estimating a 50% reduction in energy consumption, Cellura et al. (2017) for a rural building in Sicily (Italy).

Gigliarelli, Calcerano, and Cessari (2017), focused on a multiscalar approach supported by a HBIM platform and further analysed the BIM to BPS interoperability on historical buildings applications (Gigliarelli et al. 2017; 2019).

Despite the extensive use of numerical tools and particularly whole building energy modelling and CFD software, a number of researchers have expressed concerns regarding the predictive accuracy of such tools. Huerto-Cardenas et al. (2020) reviewed the main approaches used by researchers for BPS model validation with special reference to historical buildings through microclimatic parameters, highlighting the main issues and advantages of the different methods reviewed and defining suitable validation thresholds.

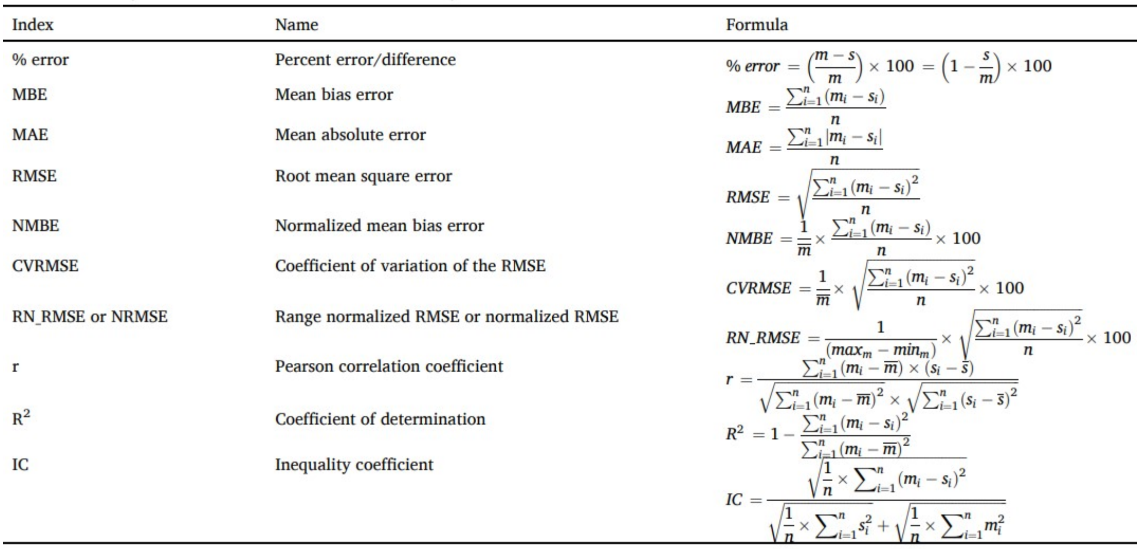
4 MODEL CALIBRATION APPROACHES

The use of dynamic simulation tools represents a great opportunity to predict the behaviour of extremely dynamic systems such as buildings. However, as models always represent a simplification of real cases, the reliability of predictions provided by simulation models requires a thorough calibration process. The ASHRAE Guildeline 14: 2014 defines calibration as "..*the process of reducing the uncertainty of a model by comparing the predicted output of the model under a specific set of conditions to the actual measured data for the same set of conditions*". Therefore, in-situ experimental data acquisition (e.g. energy consumption data or environmental conditions) is imperative in order to compare the predicted output of the model to the actual measured data.

In the case of historic buildings for which building construction is often little known, the calibration phase is of particular importance (Roberti, Oberegger, and Gasparella 2015). However, there is no established methodology or indicators for estimating the level of accuracy of models. Huerto-Cardenas et al. (2020) who reviewed the challenges regarding validation of dynamic hygrothermal simulation models for historical buildings, report the increasing use of microclimatic parameters for calibration and validation purposes in heritage BPS. This is mainly related to the availability of environmental data that are acquired through high-accuracy measurement equipment for occupants' thermal comfort assessment or risk-assessment of building materials and objects. An additional reason for using microclimatic parameters is the lack of energy consumption data, generally adopted in the model validation. This latter issue can be attributed to the absence of heating/cooling systems, which is often the case for many historic buildings, or due to difficulties in retrieving the energy consumption data. The following are often used to provide more accurate model inputs and help calibrate the model: whole building energy consumption, indoor air temperatures, in situ material properties, laser scanning of building geometry and blower door pressurization tests of airtightness (Webb 2017). Yet, the most frequently used microclimatic variables involved in model calibration are: indoor dry-bulb air temperature (Ta) and Relative Humidity (RH) (Huerto-Cardenas et al. 2020). In the study of Rajčić, Skender, and Damjanović (2018), three categories are used for the estimation of the prediction accuracy: excellent, acceptable and low. The difference between simulated and measured data is interpreted as "excellent" when it lies within ± 1 °C and ± 5% from the median for temperature and relative humidity respectively, "acceptable" when values fall within ±3 °C and ±10% from the median, while "low" when both values are out of these ranges.

A summary of the main uncertainty indices for estimating a model accuracy is provided in Table 1. ASHRAE Guildeline 14: 2014 recommends the use of the following indicators for calibrated simulations: Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) and the Normalized Mean Bias Error (NMBE). The monthly thresholds are ±5% and 15% for NMBE and CVRMSE respectively. The hourly ones are ±10% and the 30%.

Table 1: Main uncertainty indices used to evaluate the accuracy of BPS model, based on the statistical analysis of measured (m) and simulated (s) data. Source: Huerto-Cardenas et al. (2020)



Index	Name	Formula
% error	Percent error/difference	$\% \, error = \left(\frac{m-s}{m}\right) \times 100 = \left(1-\frac{s}{m}\right) \times 100$
MBE	Mean bias error	$MBE = \frac{\sum_{i=1}^{n}(m_i - s_i)}{n}$
MAE	Mean absolute error	$MAE = \frac{\sum_{i=1}^{n}\lvert m_i - s_i\rvert}{n}$
RMSE	Root mean square error	$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}}$
NMBE	Normalized mean bias error	$NMBE = \frac{1}{\overline{m}} \times \frac{\sum_{i=1}^{n}(m_i - s_i)}{n} \times 100$
CVRMSE	Coefficient of variation of the RMSE	$CVRMSE = \frac{1}{\overline{m}} \times \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \times 100$
RN_RMSE or NRMSE	Range normalized RMSE or normalized RMSE	$RN\_RMSE = \frac{1}{(max_m - min_m)} \times \sqrt{\frac{\sum_{i=1}^{n}(m_i - s_i)^2}{n}} \times 100$
r	Pearson correlation coefficient	$r = \frac{\sum_{i=1}^{n}(m_i - \overline{m}) \times (s_i - \overline{s})}{\sqrt{\sum_{i=1}^{n}(m_i - \overline{m})^2} \times \sqrt{\sum_{i=1}^{n}(s_i - \overline{s})^2}}$
R^2	Coefficient of determination	$R^2 = 1 - \frac{\sum_{i=1}^{n}(m_i - s_i)^2}{\sum_{i=1}^{n}(m_i - \overline{m})^2}$
IC	Inequality coefficient	$IC = \frac{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n}(m_i - s_i)^2}}{\sqrt{\frac{1}{n} \times \sum_{i=1}^{n} s_i^2} + \sqrt{\frac{1}{n} \times \sum_{i=1}^{n} m_i^2}}$

Roberti, Oberegger, and Gasparella (2015) proposed a calibration methodology based on the minimization of Root Mean Square Error (RMSE) through particles warm optimization algorithms implemented in the Genopt software and apply it to a medieval building located in the historic centre of Bolzano (Italy). The results obtained a remarkable accuracy of the model, that was validated on hourly indoor air and surface temperatures in winter. Coelho, Silva, and Henriques (2018) discussed a validation process of historic building simulation models by comparing measured and simulated temperature and water-vapour pressure quantifying Coefficient of Determination (R^2), coefficient of variation of the root mean square error, normalized mean bias error and goodness of fit. They case-study that was presented is a 13th century church in Lisbon (Portugal), whose indoor conditions were monitored over a year. The authors conducted a sensitivity analysis for three parameters; namely, air change rate, solar heat gain coefficient and short-wave radiation absorption coefficient. They concluded that the best results are obtainable by considering monitored weather file rather than data provided from databases, and that the parameters of soil and slab interface temperature have a significant role.

Cornaro, Puggioni, and Strollo (2016) suggested retrofit solutions for a complex historic building in Italy by using numerical tools coupled with data obtained through a short term monitoring campaign. Pigliautile et al. (2019) discussed an innovative methodology based on experimental monitoring and dynamic simulation, in order to assess the impact of passive solutions on occupants’ thermal comfort and artworks preservation. The case-study considered was the castle of Pieve del Vescovo, located near Perugia (Italy). The simulation model was performed via DesignBuilder software and EnergyPlus engine. The iterative calibration process involved the modification of the external wall materials’ width and the internal thermal gains. The statistical analysis of the calibration phase considered mean bias error and root mean square error.

De Rubeis et al. (2020) analysed the thermo-hygrometric conditions of the church of Santa Maria Annunziata of Roio in L’ Aquila (Italy), both for artworks preservation and occupants’ comfort. The analysis was carried out by means of EnergyPlus coupled with Design Builder software. In this case, the weather file used for the simulation was created using the data measured by a nearby weather station (i.e. dry bulb temperature, wind speed, atmospheric pressure, relative humidity, and solar radiation). The approach employed in their work is divided into two steps: The first calibration phase of the model was performed by comparing measured and experimental indoor air temperature, and manually and iteratively varying parameters of the model, namely temperature setpoints and air leakage, to improve its accuracy. In the second phase, the ability of the calibrated model to predict the behaviour of the building was assessed through the statistical indicators of Mean Bias Error (MBE), Coefficient of Variation of the Root Mean Square Error (CV(RMSE)), the deviation between simulated and measured indoor air temperature trends and the Coefficient of Determination (R^2).

An additional parameter with significant impact on potential differences between the modelled (theoretical) and the actual energy performance of buildings, in general, is occupant behaviour. While this parameter has been studied (Brohus et al. 2010), in the case of historic buildings user-driven energy efficiency remains problematic (Berg et al. 2017). Research and empirical data remain insufficient, while the existing methodologies assessing occupant behaviour are predominately qualitative. Certain interplays between user-related energy consumption and awareness of a buildings' cultural heritage values are reported, calling for more quantitative approaches regarding the occupant behaviour in heritage buildings (Berg et al. 2017; Kavgic et al. 2010).

5 OPEN ISSUES REGARDING THE APPLICATION OF A SIMULATION-BASED DESIGN APPROACH IN HISTORIC BUILDINGS

The term simulation-based design refers to a process, in which simulations are the main tool for evaluation and verification, aimed at eliminating inefficient design scenarios with the least possible waste of resources (Mefteh 2018). Given that the impact of strategic decisions on the energy and environmental characteristics of buildings, simulation-based design should be a fully integrated tool in the decision-making process regarding architecture (Reiser et al. 2008; Lechner 1991). In order to apply a simulation-based design approach to the built heritage, several points still need to be thoroughly addressed. Among these are:

1. The uncertainty of the data measured on site for the characterisation of the building materials to be used in the energy modelling;
2. Simplifications and assumptions, mainly referring to:

- complex and irregular geometries (most modelling software require simplifications of the building shape, that sometimes fail to adequately represent the complexity of heritage buildings and the number of surfaces, and consequently accurately calculate the energy flow between them);
- the lack of homogeneous and standardized construction elements (this might correspond either to the case of complex façades with several historical phases, or the case of a single wall with irregularities (Roberti, Oberegger, and Gasparella 2015), which often may be deteriorated or partly damaged and therefore may have variable thermophysical properties);
- the inertial behaviour of the building mass, which requires specific corrections and precautions in order to be adequately simulated by software created to simulate buildings constructed based on other structural systems than massive load bearing elements (Mazzarella and Pasini 2017);
- important envelope moisture buffering and related complexities to its calculation (Paolini et al. 2016);
- thermal stratification in large spaces (Webb 2017);
- occupant behaviour that is subject to social, economic and cultural values and insufficiently documented in the case of historic buildings (Berg et al. 2017);

3. The need to build a "critical" database of case studies, and of historical wall stratigraphies with thermophysical characteristics to help energy modellers with the definition of those charcteristics where desctructive tests are not available, and more in general to help consolidate the energy modelling approach on historical buildings, in order to identify “groups” of particularities (if any), tendencies and reverse “*the lack of publicly available detailed data relating to inputs and assumptions*“ (Kavgic et al. 2010);
4. The need for a reflection on the limits of a deterministic approach (deriving from simulation tools) applied to naturally heterogeneous cases, such as the ones of historic buildings. The above challenge calls for an approach that is tolerant to the ambiguities / limits of knowledge, inherent in the input data of the modelling of a historic building (with reference also to a possible probabilistic approach). Knowledge transfer from the diagnostic phase of the conservation process where there is a strong link between hard science specialists, humanities and conservation experts would also be beneficial, to help finding a compromise between different analysis systems approaches, to be used in parallel for the reconstruction and the energy and environmental behaviour of the built heritage. Simulation-based design on built heritage should follow therefore the path of other disciplinary field such as the structural diagnosis (Croci 2000), that was capable to find a methodological compromise between procedures that despite their uncertainties represent to date the best possible formulation of a problem based on data, hypothesis and interpretation (Gigliarelli et al. 2019);
5. The need to develop an interdisciplinary debate on the subject, allowing for the integration of different views and competences;
6. The need to create a set of guidelines based on the existing literature on the calibration and validation of energy models of historic buildings (Roberti, Oberegger, and Gasparella 2015; Huerto-Cardenas et al. 2020), while respecting the "case by case" approach according to the complexity of each case. This is important in order to identify the best energy diagnosis path to use (including not only application but also economic and time constraints), according to the principle of gradual complexity of the analyses performed in relation to the gradual deepening of the level of information required for a specific purpose.

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