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# Current practices and open issues on the whole-building dynamic simulation of historical buildings: A review of the literature case studies

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## ABSTRACT

Whole-building dynamic simulation has been increasingly adopted as a tool to non-invasively investigate possible strategies to improve energy efficiency, thermal comfort, and conservation of historical buildings. Several critical assumptions are needed to cope with insufficient input data and limitations in simulation models, therefore the modelling approaches implemented by researchers are inhomogeneous and customised for each case study. A review of the literature was conducted to collect common patterns and replicable solutions, based on the case studies reported in scientific journals published between 2011 and 2022. The discussion covers all the key stages in the simulation process, from information gathering to the analysis of the target outcomes, highlighting current practices and open issues. The resulting informative panorama and technical discussion are intended to assist scholars and specialists in approaching the dynamic simulation of historical buildings as well as stimulating a debate toward standardisation and consolidation of a robust scientific community in the field.

## 1. Introduction

The construction sector, with its burden of energy consumption and emissions, is increasingly pivotal to transitioning away from fossil fuels, as recently agreed at the United Nations Climate Change Conference COP28 [1]. Built heritage, mobilising society and strengthening social inclusion [2], can play a crucial role in the green transition [3], thus acting as a beacon for the construction sector thanks to its scientific advancement and cross-fertilisation potential. According to the definition proposed in the EU project EFFESUS (2012–2016) [4], historical buildings are constructions built before 1945 using artisanal and pre-industrial techniques. Based on the European legislative and regulatory point of view [5], only those buildings having a relatively high degree of physical integrity as well as recognised historical and cultural features (e.g., listed as Architectural Heritage) can be strictly considered as “historic”. Within the European building stock, historical buildings are neither the most numerous nor the most energy-consuming portion [6], because they generally integrate passive strategies (e.g., heavy thick walls with high buffering capacity) to adapt to local climatic conditions [7]. However, the increase in comfort standards has made no longer acceptable thermo-hygrometric conditions that once were [8], and the overall share of energy consumption and emissions in Europe represents more than 20 % [7]. The attention to energy and environmental improvement of historical buildings [9,10] is rising in the European Union agenda [3,11,12], making it central to facing the challenge of climate change as urged by the Intergovernmental Panel on Climate Change (IPCC) [13]. Since one of the most efficient ways to promote the conservation of historical buildings is to keep them in use [7,14], also safeguarding historical urban areas from abandonment [15], the energy efficiency aspect can no longer be dissociated from their overall management [9,16].

Conservation of built heritage entails activities aimed at enhancing its knowledge, orienting critical renovation design, and assessing the impact of climate change on movable and immovable cultural property [17]. The international Charters of Athens (1931) and Venice (1964), together with the Nara conference (1994) that encouraged advanced surveying techniques and scientific diagnostic applications, established a comprehensive framework and guidance on architectural conservation [18]. According to the Granada Convention (1985), also the concept of enhancement has been internationally acknowledged as the process aimed at facilitating accessibility and participation and improving knowledge dissemination and public perception of built heritage [19]. A truly interdisciplinary approach was solicited by the EU Open Method of Coordination (OMC) group of experts to minimise the risk of maladaptation, i.e., accidental losses or damage caused by adaptation measures [12]. Indeed, flawed decisions may acquire criminal relevance in the

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event of significant losses to the heritage assets and, in countries equipped with advanced bodies of legislation for the safeguarding and protection of cultural heritage, it might be mandatory to be able to demonstrate that any intervention was adequately informed and scientifically grounded [20]. International network organisations, such as the Climate Heritage Network, and initiatives, such as the New European Bauhaus, have raised attention to the need for more sustainable and interdisciplinary conservation strategies [11].

Within the EU legislative framework to boost the energy performance of buildings, the Energy Performance of Buildings Directive (EPBD) requires finding a cost-effective trade-off between investments and energy savings throughout the lifecycle of a building. The first version of the EPBD was published in 2002 (Directive 2002/91/EC) and then it was recast in 2010 and 2018 to improve clarity (Directives 2010/31/EU and 2018/844/EU). A revised EPBD version was released in 2024 (Directive 2024/1275/EU) as part of several legislative proposals to meet a minimum of 60 % reduction in greenhouse gas emissions by 2030 compared to 2015 and to achieve climate neutrality by 2050. In the EPDB, the specificities of historical buildings are recognised, and exceptions are applicable, i.e., they can refrain from complying with certain minimum energy performance requirements because of their special architectural or historical merits. The standard EN 16883:2017 provides guidelines for the sustainable improvement of the energy performance of historical buildings while respecting their heritage significance [21].

Building Performance Simulation (BPS) and Building Energy Modelling (BEM), compared to previous methodologies of building performance optimisation [22], introduced the possibility of treating buildings as integrated systems rather than the sum of elements designed and optimised separately [23]. Whole-building dynamic simulation, hereafter named dynamic simulation, involves time-varying parameters, flexible modelling capability, integrated performance assessment (e.g., energy, comfort, daylighting), and evaluation of innovative design solutions [24]. While the simplified dynamic method of ISO 52016–1:2017 [25] can only approximate to some extent the results of dynamic simulations [26], detailed multi-zone dynamic simulation models assume uniform air distribution in each zone, solving mass and energy conservation equations with less computational costs and allowing to carry out diachronic analyses under transient boundary conditions and over longer time spans. BEM is currently in an upward trend in dynamic simulations, but much remains to be studied about occupancy behaviour, building renovation, nearly Zero Energy Buildings (nZEB), and interoperability with building management systems such as Building Information Modelling (BIM) [27].

Building simulations have been increasingly used for the energy and environmental improvement of historical buildings, also thanks to the significant endowment by strategic documents providing practical guidance such as those developed within European projects such as 3ENCULT [28], SECHURBA [29], EFFESUS [4], RIBUILD [30], and more recently BEEP [10]. According to Ref. [31], dynamic simulations are recommendable in the case of historical buildings as they consider the thermal inertia of the traditional massive structures [32,33] and allow to comprehensively simulate their complex response to the real outdoor environment [34], also unlocking the possibility of a more realistic assessment of HVAC systems to optimise their performance [35]. As a complement, different scale-dependent approaches (such as those involving single-wall hygrothermal models [14]) can be used to sharpen the focus on the 2D behaviour of the building envelope [17], particularly in cases where issues of conservation are a concern. The outputs of the dynamic simulations of historical buildings (e.g., energy consumption for heating and cooling and indoor climate variables) can be used for the assessment of energy efficiency [7], thermal comfort [36], and conservation [37], i.e., for the diagnostic and prognostic assessment of the effect of indoor climate conditions in terms of mechanical, chemical, and biological decay risks for the historical buildings and the collections they house [38]. Considering the lifespan of historical buildings and in view of the ongoing climate change, researchers have started to assess the impact of future climate scenarios for planning timely, effective, and climate-change-proofed adaptation strategies [17]. Moreover, interoperability with optimised workflows based on Heritage Building Information Modelling (HBIM) [39] and integration with tailored Non-Destructive Testing (NDT) campaigns [40] can effectively support the energy and environmental improvement of built heritage.

Simulating the thermal and hygrothermal behaviour of historical buildings can be particularly challenging due to the difficulties that may arise in the accurate determination and representation of the building features, including geometry and envelope materials [41]. Indeed, historical documentation is frequently incomplete or unavailable, and NDT techniques compatible with built heritage are still not fully capable of quantitatively assessing the material properties required as inputs in building simulations [42]. The lack of homogeneity in the envelope layers (e.g., due to construction changes that occurred over many years) and the conservation state resulting from ageing and deterioration are other factors enhancing complexity [41]. Moreover, it could be also necessary to properly consider the hygroscopic capacity of historical porous materials to exchange moisture, as traditional steady-state methods might overlook condensation phenomena and the hygrothermal assessment of the envelope. According to ASHRAE Guidelines 14–2014 [43], calibration is the process of reducing the discrepancies between simulated and measured data by properly adjusting the input parameters, while validation is the operation needed for determining the accuracy of a model in reproducing real phenomena, based on its intended uses. The uncertainty of building models can be reduced through calibration and validation based on the comparison of measured variables with the same outputs predicted through the model under a specific set of conditions [44]. Due to the inherent aleatory and epistemic variability of both the inputs and the models, performance gap is a growing area of research in whole-building dynamic simulation of historical buildings [45]. The need to systematise solutions supporting a whole-building assessment of historical buildings requires the definition of an integrated, adaptable, and consistent evaluation method [46]. The historical buildings – although highly inhomogeneous – share certain characteristics that can still be generalised [6], but no complete and deep review of the main issues related to the use of simulation tools for historical buildings has been developed yet [41]. Therefore, among the auspices from the experts in this field, there is the call for a standardisation of the terminology, procedures, and approaches adopted when dealing with real case studies.

This literature review aims to define a comprehensive methodological framework for performing whole-building dynamic simulations of historical buildings. Despite the timely and strategic potentialities of their application, there is still little agreement around the modelling approaches, the validity of their assumptions on built heritage, and the ways to overcome inherent constraints and limitations. Although some review articles have been already dedicated to specific aspects of the topic (e.g., envelope representation [41], model calibration [44], energy efficiency [7], thermal comfort [36], and conservation [37]), an integrated perspective is still missing in the research community, leaving partly unsolved for the operators the issue of delivering the simulation process to the end. Moreover, all these review articles concluded that the field is yet far from being systematised and, combined with the uniqueness of historical case studies (which require tailored approaches), it remains challenging to cope with insufficient data and modelling constraints and to formulate appropriate critical assumptions. The panorama of case studies in the literature is highly fragmented and variegated due to the inhomogeneity of approaches, expertise, and sensibility to the heritage needs. Therefore, reproducibility is hindered by the lack of uniform detail on modelling choices and workarounds, which require an inevitable burden of discretion as well as a high level of competence. To this scope, pertinent case studies in the literature were analysed to identify and bring together the best practices followed in the dynamic simulation of historical buildings, ultimately to support the definition of best-compromise solutions to address the complexity of the topic. With the aim of facilitating scholars and specialists to build upon previous experiences, relevant approaches and recommendations in the available literature were collected and discussed in light of the specificities of built heritage with respect to modern and existing buildings. To the best of the authors' knowledge, this is hitherto the first systematic review confronting with such extensive matter and embracing the whole simulative process of historical buildings from information gathering to the analysis of the target outcomes. We believe that our effort to systematise an updated state of the art can contribute towards the standardisation of the decision-making process and the establishment of a common ground for future research to profitably bridge current gaps and set further research challenges.

## 2. Sampling process and selection of relevant articles

This paper is based on an extensive critical review of relevant documents about the whole-building dynamic simulation of historical buildings accessed through the Scopus database. The Scopus database was chosen as it is one of the most widely used databases for bibliometric analyses together with Web of Science, with which it shares more than 99 % of the indexed journals while maintaining a higher coverage in the interdisciplinary areas [47].

The terms used for retrieving the documents from Scopus were chosen to cover possible alternative ways in which researchers have addressed the topic, specifically including both "historical" and "historic" attributes of the buildings. The choice is to encompass the wider range of built heritage; the inclusion of both attributes is motivated by the sometimes-uncertain use of the terminological difference between "historical" and "historic" attributes and by the fact that they can share traditional construction characteristics influencing modelling issues.

The database was first queried on all its fields using the following string: ALL ("dynamic simulation" AND "historical building*"). The documents retrieved from this query were used for an exploratory analysis aimed at identifying recurring keywords used to address the reviewed topic. It was found that both thermal and hygrothermal numerical studies are relevant for the study of historical buildings' performance. Moreover, historical buildings are often referred to using equivalent expressions such as "historic* building*, "built heritage", or "heritage building*". To extend the initial subset, targeted combinations of the keywords "thermal simulation", "hygrothermal simulation", "performance simulation", and "historic* building*", "built heritage", "heritage building*" were searched to query the database on the TITLE-ABS-KEY fields. More than 570 documents matched these parameters, beyond which an additional subset of 47 articles was attached by searching cited references. Then, duplicates were removed from the identified subset, and 438 documents were selected to be screened by title and abstract. Studies addressing only the characterisation of construction materials, monthly quasi-steady-state simulations based on ISO 13790:2008 [24], and Computational Fluid Dynamics (CFD) without any description of the dynamic simulation models of historical buildings were discarded from the analysis. Moreover, since the database query returned several investigations addressing the 2D hygrothermal simulation across individual building components (rather than the building as a whole), the screening phase filtered out these papers as beyond the reviewed topic. After the screening phase, 177 eligible documents were selected. Finally, based on full-text reading of the eligible documents, a total of 105 documents was included in the study as reporting relevant case studies on the reviewed topic (Fig. 1). The eligible review papers (7 items), since not reporting original data, were excluded from the revision but used to contextualise and discuss the results. It is worth noting that, whereas the documents retrieved in the identification step dated between 1997 and 2022, the final subset includes only documents published between 2011 and 2022, highlighting that the reviewed topic is still quite recent despite an earlier interest on the broader research field.

Among the included documents, 69 % are classified as articles (72 items), 30 % as conference papers (32 items), and 1 % as book chapters (1 item). The reviewed documents were predominantly published in journals associated with the Scopus subject areas of Engineering (Architecture, Building and Construction, Civil and Structural, Mechanical), and Energy (Fig. 2). The journals reporting most of the reviewed documents were *Energy and Buildings* (13 %), *Building and Environment* (7 %), *Energies* (6 %), *Sustainability* (6 %), *Journal of Building Engineering* (6 %), *Applied Energy* (4 %), and *Journal of Cultural Heritage* (4 %). Conference papers were mostly published on *Energy Procedia* (9 %), *Building Simulation Conference Proceedings* (4 %), *IOP Conference Series: Material Science and Engineering* (4 %), *E3S Web of Conference* (3 %), and *Journal of Physics: Conference Series* (3 %).

Fig. 3 shows a synthetic representation of the keywords chosen more than twice by the authors of the documents included in the review. Fig. 4 summarises the words or expressions (made of multiple words) repeated in the abstracts more than 6 times among the reviewed documents. In both cases, general terms were initially filtered out by a natural language processing algorithm used in the term identification stage; then, the list was manually refined to focus on the most informative terms. In the manual refinement, terms such as "dynamic simulation" and "historic* building*" have been excluded as part of the selection query, together with some generic terms (e.g., "study", "paper", "order", "use", "term", "view") and locations of the case studies.

A prevalence of energy-related keywords emerged from Fig. 3 (e.g., "energy efficiency" = 26 occurrences, "energy retrofit" = 11 occurrences, "energy saving" = 6 occurrences), with this topic being the most addressed in the reviewed documents since 2016 (cited in 41 % of total), in line with [7,37]. Thermal comfort (6 occurrences), model calibration (5 occurrences), and climate change (5 occurrences) have more recently attracted attention, as testified by the literature reviews on these subjects published between 2020 and 2022 [36,38,44]. Durability has

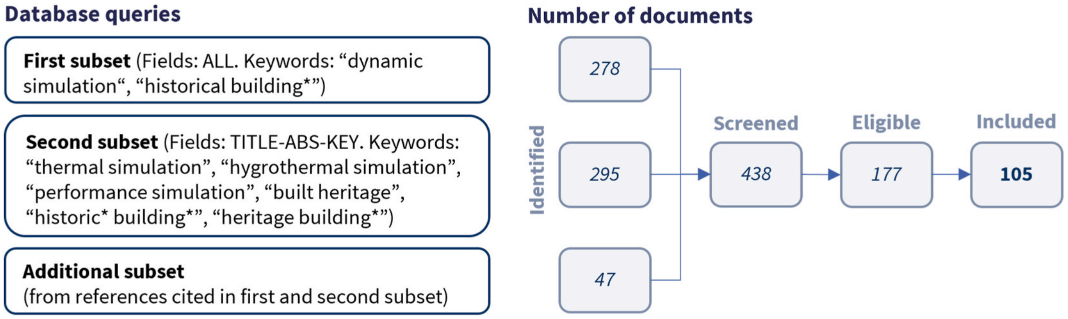

Fig. 1. Pipeline of the literature review from Scopus database and number of documents per process step. After the identification step, duplicates were removed to select documents to be screened by title and abstract. The eligible documents based on their relevance to the reviewed topic were then assessed by full text to obtain the final subset of documents included in the review.

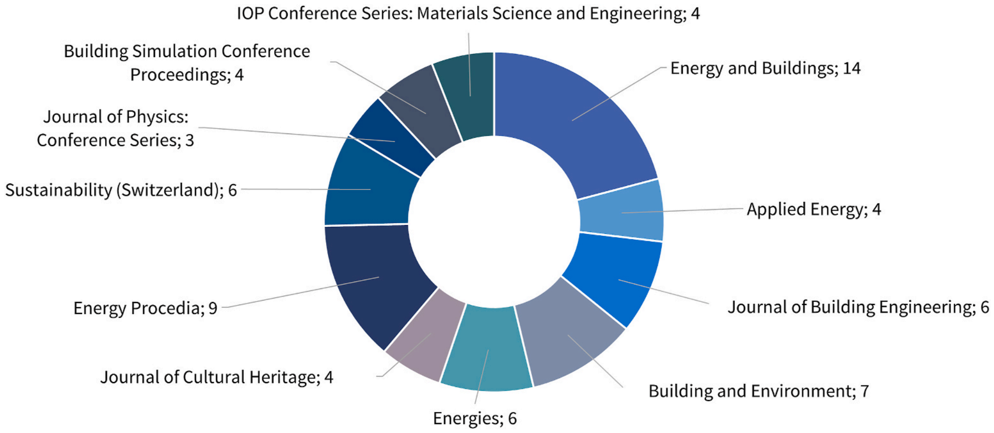

**Fig. 2.** Overview of the scientific journals reporting at least 3 reviewed documents.

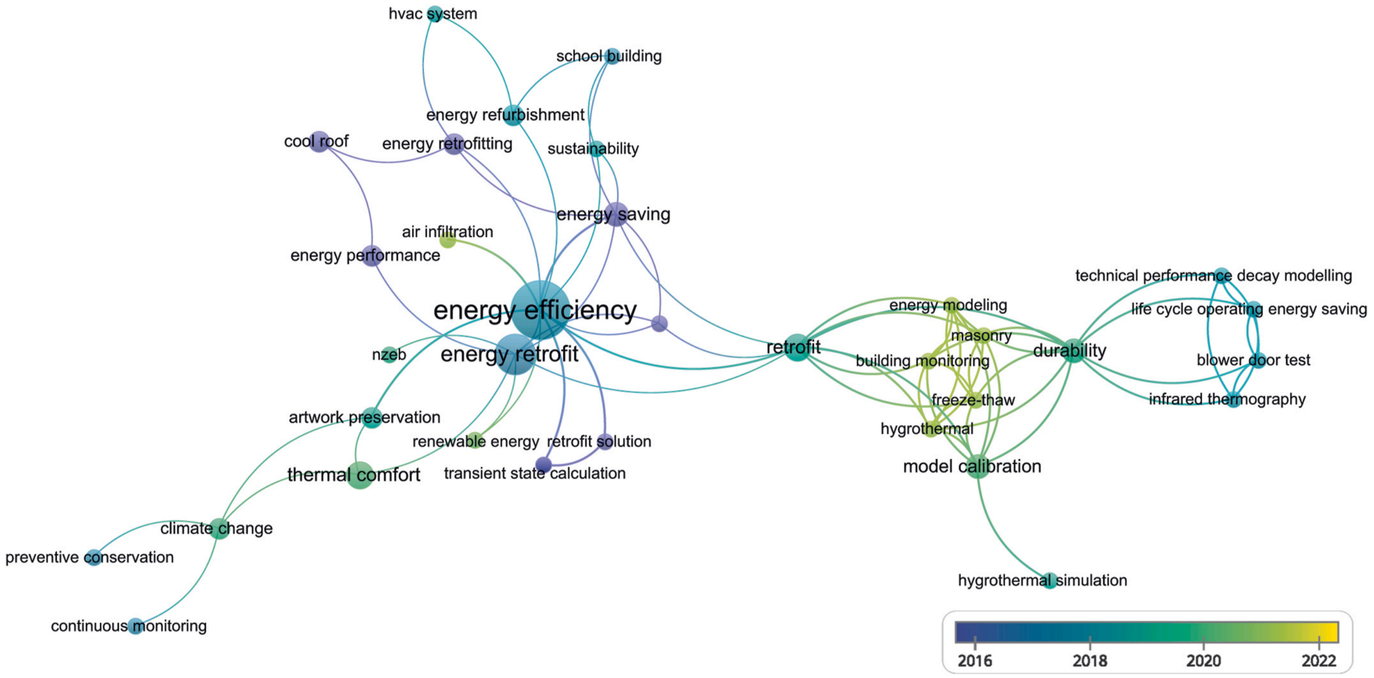

**Fig. 3.** Network visualisation of the keywords chosen by Authors (used more than twice) in the 105 documents included in the literature review, produced with VOSviewer version 1.6.18. The criteria followed to refine the list of words were specified in the text.

gained increased attention since 2018 in terms of NDT analyses (such as infrared thermography and blower door test), lifecycle operating energy saving, and technical performance decay modelling. Currently emerging topics are hygrothermal simulations and building monitoring (also connected with the evaluation of masonries and freeze-thaw cycles), accompanied with air infiltration and renewable energy solutions linked to energy efficiency. Some contexts to discuss these latter topics in relation with the dynamic simulation of historical buildings can be found in Refs. [41,44,48].

The evolution in the research field can be further appreciated in Fig. 4, showing an earlier prevalent interest in energy efficiency and performance (“energy” = 53 occurrences, “energy efficiency” = 42 occurrences, “energy performance” = 33 occurrences, “energy saving” = 31 occurrences) and improvement interventions (“intervention” = 44 occurrences, “improvement” = 32 occurrences), progressively shifting towards an increased focus on model (92 occurrences) and data (“data” = 43 occurrences, “measure” = 39 occurrences, “measurement” = 20 occurrences), particularly in terms of temperature (53 occurrences) and – more recently – relative humidity (17 occurrences). This remark complements the recent research interest observed in Fig. 3 on the hygrothermal model calibration, possibly hinting at the way it is approached in historical buildings. Data has also a strong link with research on users’ thermal comfort (52 occurrences), which indeed presents specific complexities in the case of historical buildings [36]. Finally, the earlier studies on the relationship between indoor climate (“indoor microclimate” = 10 occurrences, “environment” = 7 occurrences, “indoor climate” = 12 occurrences) and artwork preservation (“preservation” = 32 occurrences, “conservation” = 18 occurrences, “artwork” = 21 occurrences) have been lately developed into the assessment of damage and degradation risks (“risk” = 28 occurrences, “degradation” = 17 occurrences, “damage” = 8 occurrences) and of the impact of climate change (20 occurrences), which are gaining track on the current research agenda. Quite remarkably, the word “challenge” was used in the abstract of 9 reviewed documents.

A total of 112 case studies was identified out of the 105 reviewed documents, as some of them reported data on more than one case study. The literature review was based on the analysis of the data collected about four main themes.

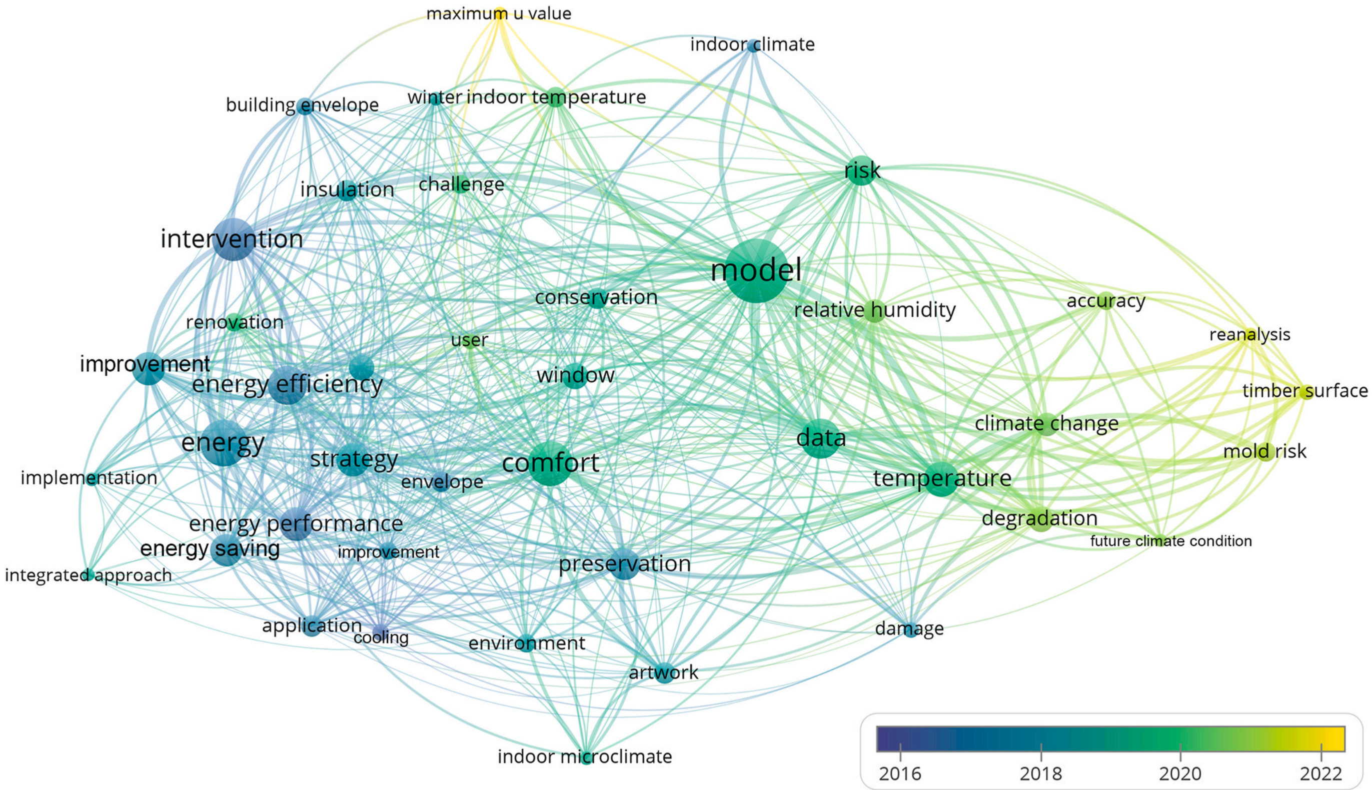

**Fig. 4.** Network visualisation of the words used in the abstracts (used more than 6 times) in the 105 documents included in the literature review, produced with VOSviewer version 1.6.18. The criteria followed to refine the list of words were specified in the text.

1) information on the case study (e.g., site, location, construction period, and function);
2) input data regarding the building features (e.g., geometry and internal spaces, airtightness, and thermal/hygrothermal properties of components), the building use (e.g., occupancy and equipment), the environmental context (e.g., site data and weather file), the measurements of the building features (e.g., infiltration and energy consumption) and indoor environmental conditions (e.g., temperature and relative humidity) in the actual state of the property (unless specified otherwise);
3) simulation approach (including simulation software tools, 3D building modellers, calculation methods, simulation time step, etc.) and calibration/validations procedures followed;
4) output data, collecting information on the assessment of the simulation results based on the aim of each study.

Special attention was dedicated to collecting the assumptions and constraints specifically related to historical buildings that the researchers reported about the whole-building dynamic simulation process.

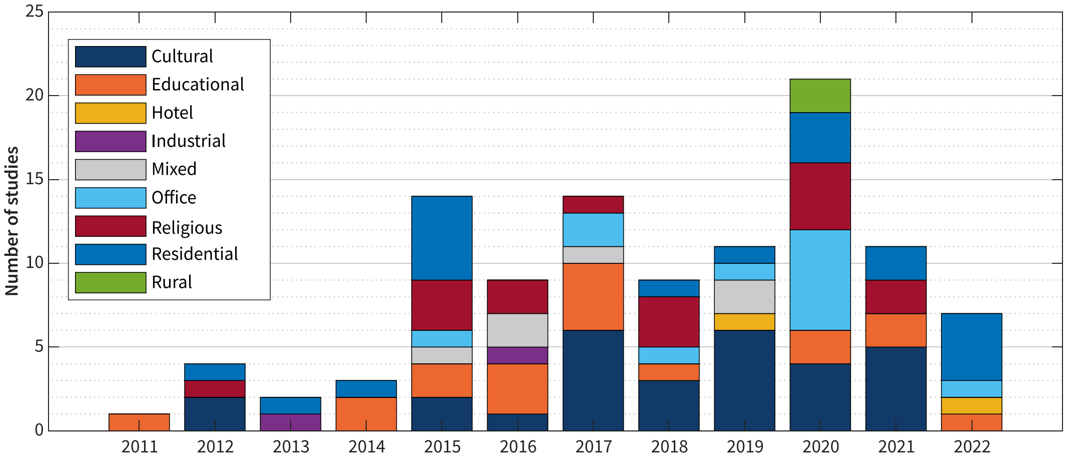

**Fig. 5.** Number of documents published per year reporting case studies on dynamic simulation of historical buildings, grouped according to their use. Buildings classified with mixed use can include offices, classrooms and cultural spaces in the same edifice.

## 3. Results

### 3.1. Case studies

### 3.1.1. Publication year and building use

Fig. 5 shows the number of case studies involving the dynamic simulation of historical buildings, grouped according to their function. Publication years were considered in the place of the year when the investigation was carried out, as this latter information was not reported homogeneously in the reviewed documents. Although the publication year may not reflect the time when the study was carried out, it can still provide a useful indication of global tendencies regarding publications in the research field.

A general increasing trend of publications is noticeable over the last decade, with a relevant leap after 2015. A prevalence of cultural sites was highlighted, including museums, galleries, and libraries (29 % of the total), followed by residential buildings (18 %), and educational spaces such as schools and universities (16 %). Religious buildings (15 % of the total) mainly include churches. In 2015, a relatively high number of case studies focused on historical residential buildings located in Italy [49–51], Portugal [52,52], Estonia, Finland, and Sweden [53] (this last paper reports a total of 68 historic houses built between 1650 and 1938, which were considered for the statistical analysis as a single case study for each of the three countries). The highest number of reviewed documents was published in 2020, and included mostly offices [54–58], cultural sites [59–62], and churches [63–66]. Mixed use refers to buildings integrating offices, classrooms and/or cultural spaces [35, 67–71]. Archaeological industrial factories [72,73], rural vernacular buildings [74,75], and hotels [76,77] built before 1945 using artisanal and pre-industrial techniques have been less frequently investigated.

### 3.1.2. Location and climate

The number of reviewed case studies per country is shown in Fig. 6. Most of them are located in Europe with the only exception of the research works performed in Saudi Arabia [62,77], and Canada [78]. Remarkably, almost 60 % of the studies were carried out in Italy. Fig. 6b shows the geographical distribution of the reviewed case studies together with their current climate classes according to Köppen-Geiger classification maps [79] (except for [78] in Canada, outside the represented area). More than 90 % of the total reviewed case studies resulted to be in areas associated with temperate climate classes (i.e., Csa = 48 sites = 43 %, Cfa = 21 sites = 19 %, Cfb = 10 sites = 9 %) and cold climate classes (i.e., Dfb = 25 sites = 22 %). The description to interpret the abbreviations of the Köppen-Geiger classes is provided in the caption of Fig. 6.

### 3.2. Input data

### 3.2.1. Site context and weather data

The availability of a suitable weather dataset (either from on-site outdoor observations or from local weather stations) was emphasised to be crucial for the accuracy of the simulation of historical buildings [80,81], especially when they are characterised by indoor natural free-floating conditions [82] and when their hygrothermal performance is under investigation [45]. Moreover, in dense historical urban areas the effect of neighbouring elements (urban morphology, materials, vegetation) on the indoor climate conditions was found to be significant [50,70,81–83]. For this reason, Coelho et al. [80] concluded that the best hygrothermal simulations were attained by the weather file developed with on-site data obtained from monitoring campaign.

About 20 % of the case studies employed on-site outdoor air temperature and relative humidity observations [45,54,84–87], often integrating weather measurements with other data sources for solar radiation [88–90]. Open-source cross-platform software tools for handling common tasks associated with weather files (e.g. format reading/writing, data visualisation/transformation, unit conversion) such as Elements (https://bigladdersoftware.com/projects/elements/) were used to edit and customise weather files integrating different data sources [91,92]. When on-site weather observations are unavailable, many researchers fall back on either nearby meteorological stations [49, 50,61,64,67,74,93–100], weather databases [8,55,68,73,76,77, 101–109], or weather data generators such as Meteonorm [58,60,

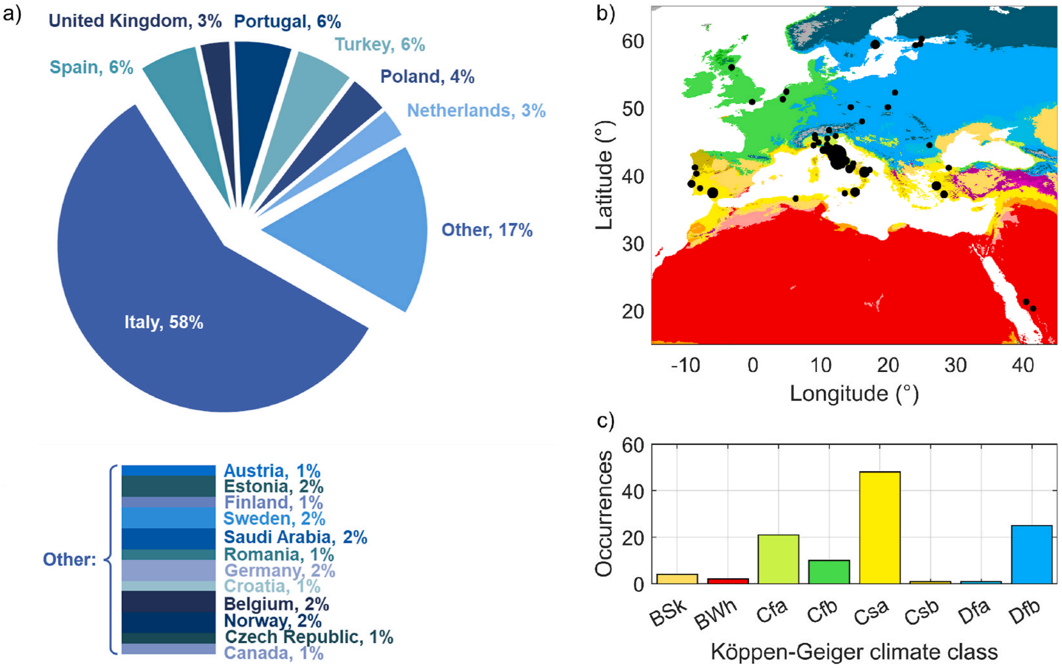

**Fig. 6.** *(a) Percentages of studies per country on the dynamic simulation of historical buildings, (b) location of the reviewed case studies (indicated as black points of different sizes according to the number of sites in the same position) and (c) number of occurrences of Köppen-Geiger climate classes (based on [79]). BSk = Arid, steppe, cold; BWh = Arid, desert, hot; Cfa = Temperate, no dry season, hot summer; Cfb = Temperate, no dry season, warm summer; Csa = Temperate, dry and hot summer; Csb = Temperate, dry and warm summer; Dfa = Cold, no dry season, hot summer; Dfb = Cold, no dry season, warm summer.*

70–72,75,81,110–112]. Standard weather data generated using multi-year weather observations, such as Typical Meteorological Year (TMY, usually generated from 15 to 30 years of historical weather data) or Test Reference Year (TRY, representing typical weather patterns excluding solar data), were used to assess the effect of energy and environmental improvement strategies (e.g. Refs. [8,77,103,104,107,108,113]), although, their use was expressly discouraged for historical buildings in Refs. [45,68,73]. Climate projections from regional models have been increasingly employed also to study indoor climate conditions at the time of construction [60,110,114] and the impact of future scenarios related to climate change [63,65,86,100,110,115,116]. The effect of different weather sources for energy performance assessment and calibration in a historical building was specifically assessed in Ref. [92], concluding that the four regional climate models tested (having horizontal grid resolutions from 1° × 1°–0.11° × 0.44°) can represent a reliable alternative when local outdoor observations are not available.

The ground temperature below the foundation is another environmental variable that may be worth considering in historical buildings, as its interaction with indoor climate conditions can introduce differences in the results [115,117], especially when validating the model [94]. Ground temperature can be modelled following ISO 13370:2017 [87,118]. Alternatively, various tailored strategies have been adopted in the reviewed case studies to appropriately consider the ground contribution: as an example, the temperature of the soil was assumed to follow a sine curve around the temperature measured at 0.5 m below ground [86] or to be constant and equal to the annual mean of air temperature.

### *3.2.2. Building characteristics: geometry, stratigraphy, and material properties*

The Surface-to-Volume ratio (S/V) was reported to have a significant impact in terms of energy consumption [35,119] due to the relative proportion between dispersing surfaces and heated air volumes. In the reviewed case studies, the typical S/V ranges approximately from 0.2 [35] to 0.5 [120,121], with values around 0.3 being the most frequently occurring [35,70,122,123]. The Windows to Wall ratio (WWR) can be used as a means to quantitatively investigate the influence of windows on solar gains and heat exchanges [62]. Although historical buildings are typically characterised by small window areas [41], it is not infrequent to find WWR well above 20 % [69,73,107,122].

The thermophysical properties of historical envelopes of the case studies were frequently investigated through multiple NDT approaches, including endoscopic examinations [74,123], heat flux measurements [73], and thermography [62,70,124,125]. In Ref. [123], the heat flux meter was used in multiple portions of the walls to average possible errors due to hidden local discontinuity and cope with construction techniques stratification over the life span of the buildings; in addition, cross-comparisons were carried out between measurements and theoretic values from the standards. In Ref. [111], the thermophysical properties were inferred through laboratory analyses on sample materials collected from a similar damaged historical building. When these properties of the envelope cannot be measured or renovation interventions (based on commercial materials) are under investigation, typical values are usually retrieved from material databases or derived from the literature [111], e.g., from standards [112], catalogues of building materials [96], and databases [87]. Licensed software (e.g., EnergyPlus, WUFI Plus, Delphin) are generally provided with their own databases, which are often used also in the case of historical buildings [66,78,95,115,126]. The MASEA database [127] was reported to be a suitable information basis, since it makes data available for the energy renovation of historical buildings [72], including the hygrothermal properties of the most widespread construction materials [87,90]. The international standards ISO 6946:2018, ISO 9869–1:2014, and ISO 9869–2:2018 are commonly used as a reference for the calculation and measurement of thermal resistance and thermal transmittance of building elements.

The main materials used in the external envelope of the case studies were reported by 82 reviewed documents (73 %) and comprise a variety of materials including masonry and timber (Table 1). Timber envelopes were reported in cold climates of northern Europe [53,95,115] and the temperate climate of Croatia [86], with most of the studies also involving the simulation of hygrothermal exchanges [86,95,115]. Concrete envelopes can be found in historical buildings built in the XIX century (e.g., mixed with stones for external and internal walls [57]). Examples of case studies with external walls made of adobe [111] and earth [91] were respectively investigated in Turkey and Portugal, where these types of vernacular constructions were common practice until the middle of the XX century.

Table 1 provides an overview of the information on various envelope materials reported in the reviewed case studies, highlighting the ones where the properties used to simulate the hygrothermal building behaviour were specified. The table is meant to be used as a reference for scholars dealing with similar envelope materials, to find insights not only on the input values attributed in specific case studies (which relate to their own history and uniqueness), but also on the thermophysical characterisation that was followed by other researchers to set those values, thus supporting more informed and tailored operative choices.

Air Changes per Hour (ACH) usually need to be measured *in situ* [53,58,88,128,142] as building airtightness (e.g., which can be compromised by air leakages of the opaque envelope and air permeability of the windows [143]) was reported to be a relevant source of uncertainty in historical building models [144]. Other frequently measured indoor variables are air absolute humidity (AH) [63], illuminance [145], concentrations of volatile organic compounds (VOC) [98,145] carbon dioxide ($CO_2$) [45,58,61,95,126,142,143,145], surface temperature [87,91,95,117], air velocity [139] and moisture content [90]. In simulation studies specifically aiming at preventive conservation, proxies for climate-induced deterioration (e.g., cracks in a painted wooden ceiling [87]) were also measured to quantitatively express the relationship between the indoor climate conditions and their effect on the heritage objects.

Since a detailed discussion related to opaque and glazed envelopes, thermal bridges, and air infiltrations in historical buildings can be found in Refs. [41,144], it was not further investigated in the present analysis.

### *3.2.3. Building use: HVAC and internal gains*

Heating, Ventilation, and Air Conditioning (HVAC) systems were reported in about 52 % of the reviewed case studies, with prevalent uses being cultural (28 % of the sites with HVAC), educational (21 %), and residential (19 %), followed by offices (11 %), and religious buildings (9 %). When exact information on the HVAC devices was lacking, their use was integrated into historical buildings' models based on the average consumptions derived from annual or monthly billings of supply contracts (e.g. Refs. [123,129]).

**Table 1**
Envelope materials in the reviewed case studies. The hygrothermal properties of the envelope materials were reported in the following papers: [87] (bricks), [45,128] (limestone), [78] (sandstone), [95] (wood).

| Envelope material (% out of 112 case studies) | | References |
|---|---|---|
| Adobe (3 %) | | [91,111] |
| Bricks (32 %) | | [54,58,61,66,71–73,81,82,85,87,94,96,100,104,107,112,121,123,126,129–135] |
| Concrete (5 %) | | [57,59,93,94,97] |
| Stone (51 %) | basalt, lava | [32,67,74,136] |
| | conglomerate | [123] |
| | granite | [122] |
| | limestone | [8,35,45,64,65,91,102] |
| | sandstone | [35,78,117] |
| | tuff | [67,90,106,120,122,123,125,139] |
| | other | [49,52,54,57,60,69,70,76,77,84,88,93,97,98,110,121,133,140,141] |
| Wood (9 %) | | [53,86,95,115] |

Due to their limited possibility of renovation interventions, the use of active systems was often identified as the only viable solution for the energy and environmental improvement of listed buildings [35,57,71,106,112]. Although we can assume that, in all the analysed articles, the HVAC system was specifically designed for the building, only few of them described how the historical case study actually influenced the system design (e.g. Refs. [84,96]), and even fewer looked into the system modelling specificities [146] also to perform calibration [54,88].

Among the case studies dealing with thermal comfort, Alongi et al. [71,120] and Cellura [71,120] evaluated the possibility of applying adaptive comfort solutions and of working in synergy with technologies such as natural ventilation. In a few cases [66,120], the design of HVAC systems was informed by the results of free running simulations aimed to investigate the passive behaviour of the building. D'Agostino et al. [106] proposed a series of intervention options for the comfort of the occupants compatible with the constraints of conservation (e.g., the impossibility modifying neither the vaulted roofs nor the majolica floors).

Several studies using HVAC systems have been carried out inside churches, also thanks to the contribution by the EU project Friendly Heating (2002–2005), where simulations were used to design local heating strategies optimised for comfort and conservation [147]. Under this project, Aste et al. [8] simulated a system of heating terminals integrated into the seats of the Gothic Basilica di Collemaggio (L'Aquila, Italy). To evaluate the use of HVAC systems in a church, De Backer et al. [146] used a simplified airflow model to estimate air stratification (since the assumption of well mixed air in the zone might not apply due to the large air volume) and a moisture buffering model to estimate the moisture exchange between air and porous materials. Muñoz-González et al. [94] integrated the simulation-based assessment of a HVAC system strategy with the hygrothermal study of the passive behaviour of historical churches in Mediterranean climate. Posani et al. [61] also reported an in-depth investigation on the way to properly simulate the thermal stratification caused by the HVAC systems.

Since historical buildings are frequently unconditioned (i.e., without any climate control devices) and require free-floating simulations, internal gains, including occupants and electric devices, were highlighted to have the potential to significantly affect the results [7,36,41,139]. Several reviewed studies considered no occupants in the model, motivating this choice either by the impossibility of quantifying the number of occupants [143] or by a scarce attendance of the building [49,64,67]. Nevertheless, the occupants' behaviour was found to be a critical uncertainty factor for a reliable estimation of the performance of improvement interventions in residential historical buildings [50] and museums [148]. To overcome the complexity of accurately reproducing the behaviour of historical buildings, Pisello et al. [113] carried out a detailed calibration procedure including occupancy schedules in rooms with different use and boundary conditions. The HVAC system design for historical buildings open to visitors and housing artworks was specifically addressed in Refs. [66,89,102]. Since historical buildings housing museums often face financial and construction limitations, Ferdyn-Grygierek et al. [143] proposed a climate control strategy without the use of expensive and extensive HVAC systems, based on natural ventilation and considering the moisture buffering capacity of the collections, suggesting that it could be generalised for similar case studies in moderate climates. Similarly, Hamid et al. [58] studied airflow management in naturally-ventilated offices to test two solutions to improve energy performance and indoor environmental quality. In the case of historical industrial facilities, equipment and machinery were considered as an equivalent imponderable factor for the simulation of energy savings [72] and, whenever referential values on internal gains were not available, hypothetical values were fine-tuned using supporting techniques such as sensitivity analysis [72].

Renewable energy systems (mainly photovoltaic systems, e.g. Refs. [57,120]) were usually addressed in terms of compatibility with the heritage values of the buildings and seem not to affect the simulations apart from the case studies including air-source heat pumps [142] or geothermal solutions [54,104].

## 3.3. Simulation approach

### 3.3.1. Simulation software and 3D modeller

Various software tools were used for the dynamic simulation of historical buildings (Fig. 7).

EnergyPlus was found to be the most used software in the reviewed case studies (53 % of the total), with some authors justifying the choice as it is an open-source dynamic simulation software that was validated according to ANSI/ASHRAE Standard 140–2011 [88]. TRNSYS was used in the 19 % of the reviewed case studies and it was employed mainly for thermal models including HVAC systems [51,55,57,60,68,70,71,84,101,103–105,112,120,149–155], with only few exceptions where free-floating conditions were addressed [73,83]), as it is a flexible tool for the dynamic simulation of plants through interconnecting modular system components [104]. WUFI Plus [45,65,66,86,95,115,117,155,156] and HAMBase [61,89,99,100], were recommended by the project Climate for Culture (2009–2014) for the hygrothermal simulation of historical buildings based on simultaneous heat and moisture transfer calculations. IDA ICE was used for both thermal [53,58,67] and hygrothermal simulations (by extending it with the HMWall model provided by EQUA developers on request) [87,90,128,157]. Compared to other simulation software tools, IES.VE has had more recent applications in historical buildings, with studies from 2018 on [75,81,135,155,158,159]. Finally, other reported tools are EDSL TAS [62,76] and BSim [160]. In a few case studies, whole-building dynamic simulation was combined with Computational Fluid Dynamics (CFD) analysis to refine the calculation of convection coefficients [134] and to study the disposition of HVAC terminals for thermal comfort [8,122,159], and with seismic performance assessment [56,123].

Most of these simulation software tools are validated by the BESTEST procedures (Building Energy Simulation Test) developed in the framework of the International Energy Agency (IEA). Geometrical constrains were regularly reported for the simulation software tools, e.g., for EnergyPlus [36,41,124], IES.VE [81], and IDA ICE [90]. Cardinale et al. [161] warned that measurement campaigns and validation are essential for dynamic software tools like EnergyPlus to properly simulate the energy and environmental performance of vernacular buildings. For the hygrothermal simulation across historical masonry walls, Gutland et al. [78] reported that EnergyPlus 8.8 is not able to simulate the hygric buffer effect of masonries exchanging moisture in the zone. Since little information is available on the differences among the available dynamic simulation software tools, tailored cross-comparisons were carried out in Refs. [68,155,162] to explore the way they may affect the outputs in historical buildings (e.g., heating loads. Temperature, relative humidity, and irradiance). Mazzarella et al. [163] tested the use of conduction transfer functions for heat conduction resolution in EnergyPlus 8.6 and TRNSYS 17 when dealing with massive walls of historical buildings,

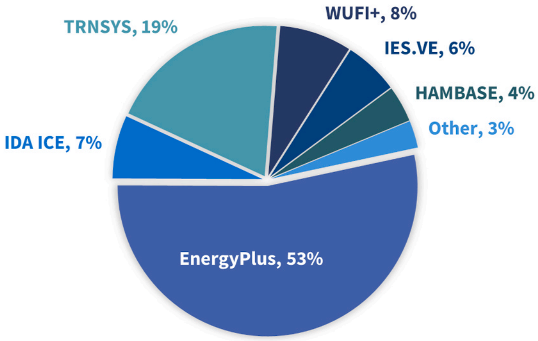

**Fig. 7.** Percentage of simulation tools used for the dynamic simulation of historical buildings.

highlighting that the different algorithms can affect the obtained results (i.e., wall temperature and density flux). Pompei et al. [68] highlighted that in TRNSYS 16 the number of properties that can be assigned to building layers might be insufficient for a detailed representation of the characteristics of the materials. Gori et al. [155] compared EnergyPlus, IES.VE, and WUFI Plus in the hygrothermal simulation of a historic building and found that IES.VE and EnergyPlus showed similar results for energy performance and heating loads, while WUFI Plus and IES.VE were more consistent for indoor conditions and thermal comfort evaluation; moreover, they concluded that moisture-related calculations may differ across tools, leading to significantly different results in relative humidity values. Frasca et al. [162] proposed a standardised exercise, named HB0, tailored to test different simulation software tools and approaches in their application to historical buildings. The comparison through HB0 among EnergyPlus, IDA ICE, and WUFI Plus showed that differences in the amount of air mass considered in the calculation and in the convective heat transfer coefficient for vertical upward flows might be responsible for the differences found in the simulated temperature values.

Most of the reviewed documents did not report any 3D modeller for the 3D geometry of the building (54 % of the total). DesignBuilder, which is typically used with EnergyPlus, was the most used 3D modeller (34 % of the total), followed by SketchUp (11 % of the total), which - thanks to its simplified and intuitive parametric design commands [159] - was employed to build models for TRNSYS [51,57,83], EnergyPlus [131,143], WUFI Plus [45,156], IES.VE [75,159], and IDA ICE [87,157].

### *3.3.2. Simulation settings, modelling constraints and solutions*

Among the main difficulties that researchers encountered while trying to reliably model the behaviour of a historical building, there is the need to introduce geometrical simplifications without affecting the total surfaces [124], volumes [90], mass and properties of opaque components [66] influencing heat and moisture exchanges.

External walls and roofs forming the envelope of historical buildings can have greatly variable thicknesses [8,99] both along the perimeter [58,64,113] and across the height [67,69,78,112,139]. In such cases, even small differences in height and thickness may create issues in modelling the thermal zones [124]. Some typical historical building elements, such as arches [66] and vaults [136] require to be simplified to comply with software limitations, as reported for EnergyPlus [36,41], IES.VE [81], and IDA ICE [90]. Moreover, massive buildings may have internal load-bearing walls as thick and thermally conductive as the external ones [68], possibly introducing an inaccurate representation of the internal volumes, surfaces and total masses [66].

Walls [67] and roofs [123] can also present damages and/or consist of a wide range of different or unknown materials. The influence of the assumption of homogeneity underlying dynamic simulation models was investigated by Evangelisti et al. [164], which tested the capability of an approximate homogeneous equivalent wall model to reproduce the behaviour of a multi-layered wall. In some cases, researchers opted to set the thermal properties of the predominant material [88] and assumed the transmittance of the envelope to be equal to the average value calculated based on the greater thicknesses on the ground floor and the lesser on the top floor [112]. Gutland et al. [78] assumed identical thermal properties of the masonry walls, ignoring the effects of voids and the inconsistent nature of wall construction. When the thermophysical properties of external walls were mostly unknown [88], they were approximated as a function of the volumetric ratio of the components (e.g., bricks, mortar, pebbles) with respect to the total wall volume [60].

The resolution used for sub-hourly time step simulation through the conduction transfer function was found to be critical for the simulation of thick walls, as it might affect the quality of the results when simulation time step is small [163]. To overcome this issue, a conduction finite difference solution algorithm was also proposed to be used in EnergyPlus in the place of the default conduction transfer to perform more accurate calculation [97,122]. Initialisation is another factor that was deemed worth considering to properly account for massive wall inertia. The initialisation period was set according to wall thickness and materials, ranging between one week [67] and one year [61], with typical duration around 2–3 months [87,90,95]. Another aspect that deserved consideration was the software conversion of the weather file [162], whose interpolation may cause distortions to the energy simulation outputs of historical buildings. In such situations, the unwanted effect of the weather simulator due to automatic data manipulation (e.g., interpolation) was circumvented in Ref. [163] by connecting the outside surface of a wall to a data reader.

According to the reviewed documents, moisture buffering effect should not be underestimated in historical buildings [165]. Modelling coupled heat and moisture transport processes in the envelope and its interaction with the room was considered key to achieving a realistic simulation of relative humidity level and fluctuations [117]. Indeed, according to Ref. [166] the steady-state Glaser method may overlook many of the aspects that substantially affect the system because it does not consider the hygroscopic capacity of porous materials to adsorb or absorb moisture. In such a case, significant differences in humidity results were interpreted as likely generated by inaccurate moisture-related calculations [155]. For this reason, Heat, Air, and Moisture (HAM) models have been increasingly used by researchers for carrying out hygrothermal assessment in historical buildings (Figs. 3 and 4). Nevertheless, HAM models require the knowledge of thermophysical and hygric properties of historical materials, which are harder to find [90] and might need to be determined experimentally also through destructive techniques involving the collection of wall samples [167]. When it comes to simulate moisture transport across a massive envelope [128], proposed 18 layers for the external walls of a XIII-XIV century church 1.5 m thick, to obtain sufficient discretisation.

The number of zones in the building model was reported only in 43 documents out of the 105 that were reviewed (41 % of total); among these documents, 37 % (16 articles) considered a number of zones comprised between 1 and 5, 37 % (16 articles) considered a number of zones comprised between 6 and 20, and 26 % (11 articles) considered more than 20 zones. Standards such as the ASHRAE 90.1 and the Italian UNI/TS 11300–1 can be used as general guidelines for the subdivision of the building into thermal zones [112], under the assumption of well-mixed indoor air of each thermal zone. As a rule of thumb, in Ref. [45] it was underlined that the number of zones in the building model should be sufficiently high to be able to account for all the relevant processes happening therein, while [160] stressed the importance of avoiding to unnecessarily increase the simulation effort. In Ref. [91], each zone of the historical building was thermally connected to the other ones to simulate their mutual interactions. Otherwise, to reduce the computation effort, adiabatic boundary conditions were modelled between zones [78] or with adjacent buildings [32]. Considering the high thickness of the historical walls, in Ref. [138] the zones were modelled from the middle of the wall to avoid increasing the overall volume once assigned the thickness of the walls. To limit the loss of model accuracy while zoning, in Ref. [124] the internal masses corresponding to each thermal zone were checked and manually adjusted afterwards. Special attention should also be paid whenever historical buildings are not directly based on the ground; in such a case, free air flow below the building was modelled by Ref. [115] as an additional zone entirely open on the vertical sides. According to Ref. [165], when it comes to investigating the impact of heating systems in high-ceilinged historical buildings (such as churches and palaces), the air temperature stratification should not be neglected: in such a case, Posani et al. [61] vertically divided the space into different zones by using fictitious inter-zonal surfaces made of a material with high thermal conductivity and vapour permeability.

Internal masses (frequently also related to a load bearing wall masonry with thick internal partitions) are another aspect that was reported to be especially important to consider [35,62], as neglecting their contribution could cost a substantial loss in simulation accuracy [72]. In addition, it is not infrequent for historical buildings to house considerable volumes of densely-packed hygroscopic collections, having the potential to significantly affect outputs due to their not negligible hygrothermal buffering effect, e.g., in libraries and archives [156]. In a wooden church in Poland, hygroscopic materials were modelled using appropriate hygrothermal properties, minimum exchange surfaces, and average thicknesses [95]. A similar modelling issue was addressed in Ref. [98] to simulate adsorbent plasters in a XIV-century castle through the introduction of a dummy system that can guarantee an “equivalent” control of the internal environmental parameters.

### *3.3.3. Calibration and validation*

Among the 112 case studies that have been reviewed, 46 of them reported to have carried out calibration (41 % of total), and 43 studies mentioned to have performed validation (38 % of total). Among them, only less than 20 case studies reported to have conducted both calibration and validation. Calibration is usually based either on energy bills, on a monthly or yearly basis (32 % of the studies including calibration), or on indoor climate measurements such as air temperature and relative humidity (75 % of the studies including calibration). The latter approach has been increasingly adopted in the case of historical buildings (e.g., in Refs. [16,62–65,77,78,86,89,90,94,96,97,99,100,102,111,115,117,160,168,169]), as they frequently lack HVAC systems and need hygrothermal characterisation for climate-related conservation risk assessment (§3.4.3). In situ and laboratory measurements were found to be critical to accurately simulate the dynamic hygrothermal conditions of historical buildings [139]. Moreover, even when energy bills are available, according to Ref. [2] indoor climate measurements are always preferable for calibration purposes.

Roberti et al. [88] highlighted that uncalibrated historical building’s models and models calibrated only on a single performance indicator (e.g., energy consumption) might be unreliable. Schmidt et al. [108] stated that model calibration should possibly rely on hourly weather data monitored at the same time of the performance to be simulated. Indoor climate measurements on an hourly basis were preferably used to calibrate the historical buildings’ models [49,67,87,90,95]. Pisello et al. [50] calibrated through iterative modifications the model of a historic residential building in Perugia (Italy) using continuous temperature data monitored in-field, so as to consider the thermal capacity of massive walls and the low solar thermal gain due to dense concentration of buildings in the area obstructing sunlight. Timur et al. [111] assumed that the calibration could be generalised for case studies using similar simulation variables and simulation software tools. Several studies carried out sensitivity analysis to evaluate the uncertainty involved in the typical variability of thermal [45,73,88,91] and hygrothermal [78,87,90] properties of historical materials and reduce the calibration parameters. Rospi et al. [35] performed model calibration in different seasons, as a function of different S/V and exposure of three historical buildings.

Coelho et al. [45] demonstrated that the use of TMY or TRY weather files may not be suitable for the validation of historical buildings’ models, also showing the importance of considering soil and slab interface temperature. Validation of relative humidity can be more difficult than temperature [143], as the mass of hygroscopic materials (such as wooden furnishings and altars) plays a greater role in determining internal heat and moisture gains [95]. Tronchin et al. [159] claimed that comparisons of different architectural scenarios can be exempt from a specific validation as they imply only an assessment of relative differences. The most used uncertainty approaches for the validation of dynamic simulation models of historical buildings have been recently summarised in a comprehensive review [44], to which the interested reader can refer to find useful information to measure the discrepancy between measured and simulated hygrothermal performance.

## *3.4. Output data*

The main purposes of the use of dynamic simulation in historical buildings focus on energy performance (§3.4.1), thermal comfort (§3.4.2), and climate-related conservation (§3.4.3), with most of the studies trying to address more than one of these aspects simultaneously. The air temperature in the rooms (56 %) and the building energy consumption of (52 %) are the most frequently reported output variables in the reviewed documents. Among the 34 studies that considered also relative humidity (29 % of the total), more than half of them was published after 2018 [45,62,64–66,74,78,86,87,90,91,94,95,115,116,131,132,143,149,155–157].

Simulation-based assessment was effectively leveraged by several studies to evaluate renovation strategies for historical buildings, able to balance thermal comfort, energy demand, and economic feasibility [49,50,58,75,76,84,103,120,125,129,138]. The challenge to find a trade-off among thermal comfort, energy demand reduction, and conservation requirements (for buildings and collections) was investigated in Refs. [87,89,96,98,108,113,133,149,157,170]. Multi-objective optimisation strategies were leveraged in Refs. [149,157] in the attempt to find a weighted balance among aspects that might sometimes be conflicting.

The performance of historical buildings was also simulated to reconstruct a hypothesis of their originally-designed indoor conditions [60,99,159] as well as to assess the impact of future climate scenarios [63,65,86,100,115,160,171] and design appropriate adaptation strategies [172]. As reported in Refs. [9,107,111,137], this kind of investigation can also be pivotal to enhancing the sustainable management of historical buildings.

### *3.4.1. Energy performance*

HVAC systems and internal gains were found to greatly vary as a function of the use of the buildings. Several reviewed studies proposed tailored strategies to adjust the use of existing or planned HVAC systems in museums through the fine-tuning of their operative setpoints [89,143,157] to balance energy consumption reduction with human thermal comfort and conservation requirements [126,149,157]. The energy performance of historical churches in southern Europe was simulated in Refs. [94,134], highlighting the building volume, number of windows, and roof type [94] as significant factors in energy consumption. Several studies also investigated strategies to transform historical buildings into nearly Zero-Energy Building (nZEB) [68,69,112,122,134], providing an overview of their limits and potentialities. In historical industrial facilities, the lack of benchmark data was reported as a barrier to performing energy performance comparisons [72]. Finally, almost half of the reviewed case studies did not report the presence of HVAC (i.e., unconditioned historical buildings). The impact of global warming on the indoor conditions of historical buildings without cooling systems located in Central Europe was investigated in Ref. [160].

The European standard EN 16883:2017 “Conservation of cultural heritage – Guidelines for improving the energy performance of historic buildings” [46] was applied in two reviewed case studies [169,173], within Task 59 “Renovating Historic Buildings Towards Zero Energy” (2017–2021) launched by the International Energy Agency - Solar Heating and Cooling Programme (IEA-SHC). Which highlighted that a whole-building approach is necessary for defining renovation interventions based on the integrated evaluation of energy consumption, compatibility, and environmental aspects. The principles of the LEED rating system proposed by the Green Building Council (GBC) were applied to evaluate the sustainability level of conservation activities on historical buildings by Refs. [145,170]. The ASHRAE Guideline 34–2019, *Energy Guideline for Historic Buildings*, was not referenced in the reviewed case studies.

### *3.4.2. Thermal comfort*

Thermal comfort in historical buildings was mostly assessed through Fanger’s indexes [75,84,85,96,108,113,113,131,141,151,159] and adaptive comfort models (e.g., ASHRAE 55 [60,62,84,169] and EN 15251 [87,108,120]). Some case studies reported to use other indexes such as the Thermal Deviation Index [49,50], the Intensity of Thermal Discomfort [136]), and the Adaptive Temperature Limits [89]. Although extensively used in the reviewed literature, it is worth highlighting that Fanger's indexes, i.e., the Predicted Mean Vote (PMV) and the Predicted Percentage Dissatisfied (PPD), are not advisable in naturally-ventilated buildings, as confirmed by the inaccurate results reported in Ref. [36]. In two case studies, questionnaires were also used to analyse the thermal comfort of occupants [58,62].

Thermal comfort has been extensively studied in historical churches, where it was highlighted the influence of the high-volume interior spaces [141], the potential of thermal mass, orientation, spray evaporative cooling and ventilation [62], as well as active and passive environmental techniques (e.g., radiant panels for localised heating based [84], air conditioning, floor heating systems and humidifiers [64,96]). For museums, the thermal comfort of visitors was investigated also considering the specific conservation needs of the collections [84,87,89,108,113,149]. For their distinct function, simulation-based thermal comfort has been frequently investigated also in residential buildings [32,49,50,83,85,121,137], educational spaces [102,111,123,125,133,136,151,155,174] and offices [35,54,58,120,145,169]. Two studies conducted on Italian fortresses in temperate climates (i.e., Rocca Paolina in Perugia [102] and Fort Begato in Genoa [138]) reported a demand for cooling much lower than that for heating.

### *3.4.3. Climate-related conservation*

Most of the reviewed documents using dynamic simulation specifically to assess and/or improve conservation conditions of historical buildings were carried out in museums [59,87,89,90,97,110,143,149,157] and churches [63–65,94,96,117,128]. Several reviewed case studies investigated the compatibility of energy and environmental improvement solutions with heritage buildings in terms of visual appearance [49,50,111], invasiveness [57,58,84,98,106], and reversibility [54,93,103,145]. Since the adequateness of renovation solutions should consider multiple aspects simultaneously, a risk–benefit matrix was proposed in Ref. [133] for the evaluation of various retrofitting solutions.

Climate-induced risk assessment was performed in combination with whole-building simulation to investigate mechanical [64,87,94,97], biological [94,115,175], and chemical [115,149] processes threatening the durability of cultural properties. For such applications, measuring and/or calculating the surface temperature and relative humidity of building components was reported to be pivotal to increasing accuracy in the estimation of mould risk in a wooden church in Norway [115] and mechanical fatigue in a wooden ceiling in Italy [87]. Huijbregts et al. [99] coupled a hygrothermal model of a 17th-century Dutch castle with a finite element model of a wooden cabinet, to compute the strain associated with diffusive heat and moisture transfer around the object. Cavalagli et al. [110] proposed a hierarchical methodology for material degradation risk mapping and applied it to assess climate change impacts and possible structural damages in the Consoli Palace of Gubbio (Italy). The method developed in the framework of the EU project Climate for Culture was used in Refs. [86,100] to assess future conservation risk for historical buildings and collections around Europe. More recently, the impact of climate change on the conservation of historical buildings was assessed in Italy [110], Portugal, Spain, Czech Republic, United Kingdom [65], and Norway [115]. Dynamic simulation was also used to study possible mitigation strategies of climate-related conservation risks; as an example, Antretter et al. [117], proposed adaptive ventilation in two German historical buildings to lower humidity conditions and avoid both summer condensation and deliquescence cycles of ammonium nitrate in the wall plaster and stone.

## 4. Discussion and open issues

### *4.1. Case studies*

The raising trend in the reviewed publications noticeable after 2015 (Fig. 5) was probably brought by several European projects dedicated to the topic that ended or started around that period [176]. The high number of reviewed documents published in 2020 is in line with the dramatic increase in publications observed during COVID-19 pandemic [177]. Italy can be considered as the country leading the research on dynamic simulation of historical buildings (Fig. 6a), most likely thanks to the richness of built heritage [7] and the attained level of maturity of the scientific debate on conservation [18]. Fig. 6b highlighted that the current research on the dynamic simulation of historical buildings markedly focussed on temperate and cold climates, while few reviewed case studies was reported on the arid classes where a considerable number of architectural sites in UNESCO's World Heritage List are located [178]. The prevalence of journals from the engineering area with respect to the conservation area could be influenced by the current research evaluation system, promoting researchers based on quantitative metrics and discouraging publications in journals of broader fields. Moreover, a lack of an interdisciplinary community was observed around the dynamic simulation of historical buildings. An indication in this sense could be the limited use of terms and expressions strictly linked to the historical and architectural analysis of the buildings both as keywords (Fig. 3) and in the abstract (Fig. 4), hindering a fully interdisciplinary discourse. This may also affect the shape that works acquire because of filtering out interdisciplinary insights in favour of more conventional approaches. Moreover, the research challenges undertaken in the reviewed documents seem to focus more on addressing specific technical aspects related to dynamic simulation of historical buildings rather than on tackling the barriers hampering its wider usage and technological transfer. Desirable advancements in this field entail a more profitable dialogue among disciplines, which is urged to elevate the soundness of scientific research around integrated conservation strategies and sustainable management of historical buildings [10].

Workflow of the dynamic simulation process for historical buildings.

A schematic workflow of the process of dynamic simulations of historical buildings was elaborated from the analysis of the reviewed documents (Fig. 8), up to simulation-based design (i.e., the use of simulations as the primary means of evaluation of energy and environmental improvement strategies). The workflow is articulated into three main thematic areas.

- inputs (context, building characteristics, building use, measurements);
- simulation (calibration, validation, simulation-based design for energy and environmental improvement);
- outputs (depending on the aim of the study, including the improvement of thermal comfort, the reduction of energy consumption, and conservation).

For each block, the principal subjects to be addressed in the simulation are reported, together with the specific issues typically associated with the application to historical buildings (right column).

### *4.2. Input*

The analysis of the reviewed case studies highlighted that data uncertainties and accessibility (affected by constraints in time, budget, and expertise required), and the difficulty of satisfactorily translating the heterogeneity and complexity of the historical buildings into abstract model inputs are among the main issues that might be encountered when dealing with the dynamic simulation of historical buildings. The selection of the source for weather data, although greatly dependent on data availability, was often based on the scope of the simulation (e.g.,

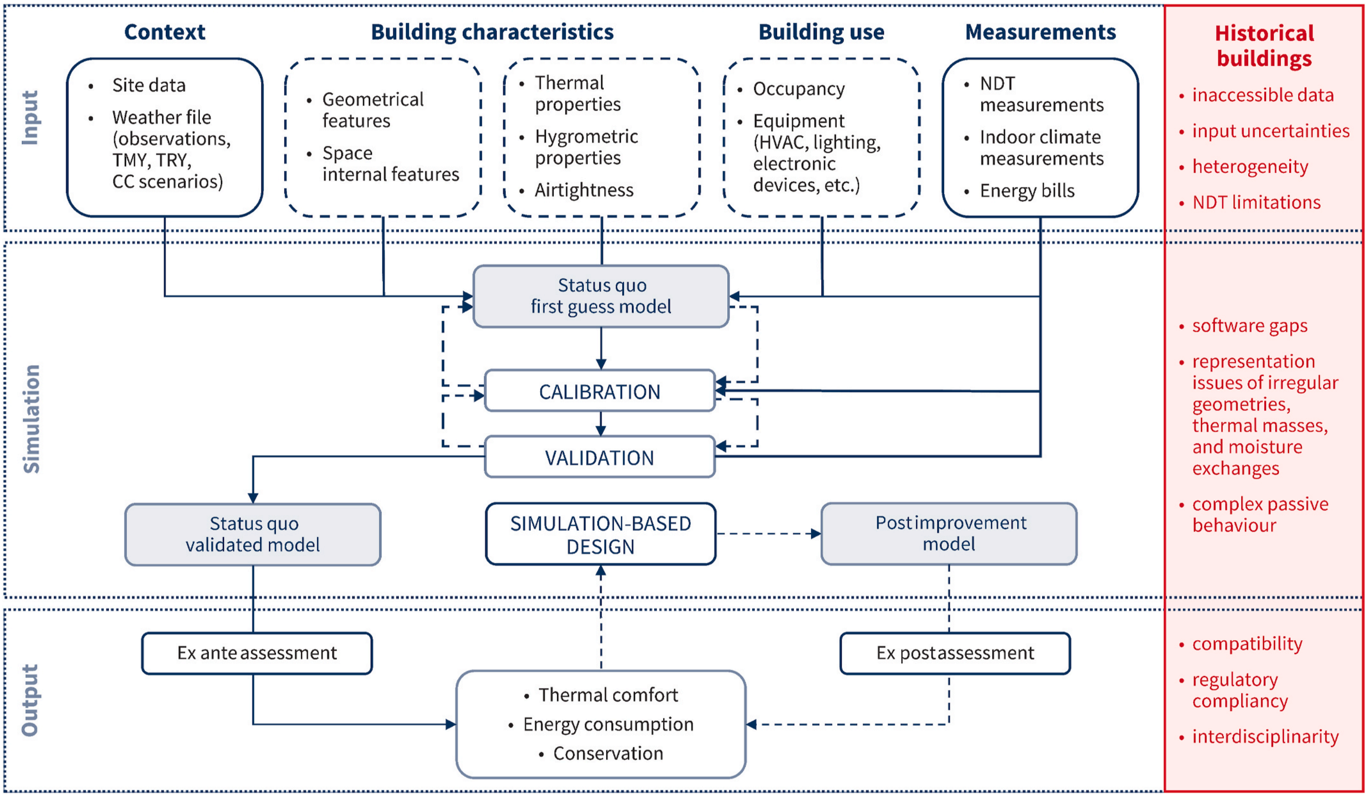

**Fig. 8.** Workflow of the dynamic simulation process articulated into input, simulation and output's thematic blocks. The main issues that might arise in the applications to historical buildings are summarised in the right box. Abbreviations: CC = Climate Change; HVAC = Heating, Ventilation, and Air conditioning, NDT = Non-Destructive Testing; TMY = Typical Meteorological Year; TRY = Test Reference Year. Dashed lines indicate the steps of the calibration, validation, and simulation-based design processes, involving hypotheses on changes of part of the inputs (represented in dashed boxes). This recursive workflow of the simulation-based design process requires the modelling of the post improvement situation, and the verification through ex post output assessment.

on-site weather observations for model calibration, multi-year weather data for energy and environmental improvement strategies, and regional climate forecasts for future scenarios). Geometrical features such as S/V and WWR were seldom reported in the reviewed documents, limiting the possibility to detect significant patterns on their impact over the performance of historical buildings. A low percentage of reviewed documents provided the hygrothermal properties of the materials used in the building envelope (Table 1) and a relevant number of them did not report any specification, possibly constituting an obstacle to a wider exploitation of this kind of studies. The use of material databases could partially solve the epistemic uncertainties related to lacking information, but experimental campaigns involving *in situ* and laboratory measurements remain critical for complex historical buildings. Moreover, since a large share of them is unconditioned, indoor climate data might be necessary in order to be able to perform model calibration. Nevertheless, measurements to gather input data for the simulations can be time-consuming and require elevated technical skills, becoming a significant discouraging factor that may hamper the acquisition of the detailed inputs needed to model historical buildings [2], especially for the technology transfer to non-academic applications.

General advisable practices in the definition of the input data of historical buildings are.

- o To prioritise measurements of the thermophysical properties over averaged values, particularly in case of thick and inhomogeneous building envelopes;
- o To choose a proper source of weather data also according to the scope of the simulation;
- o To preferably perform calibration through indoor observations of air temperature and relative humidity;
- o To consider occupancy and HVAC monitoring whenever relevant.

Further research is needed for a consolidation of the approaches to use NDT techniques for the thermophysical characterisation of the building and for the understanding of its energy and environmental behaviour for simulation purposes, as the literature on these procedures is still limited [42]. A database of historical components, integrating architectural manuals on traditional construction techniques and the thermophysical characterisation of the most widespread materials on a local basis, would be critical to providing reliable inputs to feed the simulation models as well as to limiting simulation uncertainties by using reference data for interpreting the experimental measurements. Finally, enhanced engagement of behavioural research is awaited to reduce model uncertainties in terms of occupancy patterns and to limit the undesired rebound effect after energy and environmental improvements.

### 4.3. Simulation

Modelling historical buildings entails complex methodological choices involving a wide number of critical assumptions also related to the limitations imposed by model abstractions and the narrow flexibility of simulation software tools, which might not guarantee the necessary control over the process. From the reviewed literature case studies, it emerged a shortage of detailed descriptions of the modelling choices made regarding the geometric representation of historical buildings [41] and the influence of geometrical simplifications on model uncertainty is often overlooked. A similar concern applies to adequate consideration of the internal masses of massive historical buildings, whose impact on the results (e.g., in terms of stabilisation of the internal air temperature) might not be assumed to be negligible. About the zoning of the building model, the application of standard procedures for thermal zoning (such as the one addressed in ASHRAE 90.1) may lead, in the case of massive historical buildings, to an inaccurate representation of the internal volumes, surfaces, and total masses. Varied approaches have been followed in the reviewed case studies (from single zones to highly detailed models), but the related information is often lacking although being an open issue strongly conditioned by the complexity of the case study. This could be interpreted as indicative either of the little relevance attributed by researchers to zoning and geometric aspects or of the overlooking of the subject by the specific expertise involved in these studies. Despite the unquestionable potential of HVAC integration in historical buildings, further studies are needed, particularly in the early-stage design, to help reducing the risk of damage to artworks after the implementation. The simulation-based design of the HVAC systems should involve a critical discussion related with the historical context in which the systems are applied, not only in terms of compatibility with the heritage values but also to understand whether the passive behaviour of the historical building can influence system requirements and operation. To this scope, hygrothermal simulations are preferable for a correct representation of the interactions between the systems and the building and free-floating simulations of calibrated models could be leveraged to get a better understanding of the building behaviour and to synergise the HVAC performance accordingly.

General advisable practices in the modelling of historical buildings are.

- To seek compensating the effect of geometrical simplifications (e.g., adjusting internal masses);
- To adapt model zoning to entail air thermal stratification in case of high-ceilinged buildings;
- To prefer hygrothermal models whenever there is a concern on the impact of moisture exchanges on energy efficiency [166] and durability [78], especially if climate change is addressed [172];
- To properly consider the building passive behaviour in the simulation-based design of the HVAC systems.

The objective of the simulation has a direct impact on the required level of model accuracy: relative comparisons (e.g., among different intervention strategies) can be less demanding, while the absolute evaluation of future risks and compliance with energy improvement, thermal comfort and conservation targets require refined input and more detailed and conscious modelling. In this framework, notwithstanding the need to simplify the complexity of a real building into an abstract model, the energy and environmental simulation analysis of historical buildings must be able to scale its degree of detail and adapt the modelling approach to pursue – through recursive passages of hypotheses, modelling, and verification (Fig. 8) – a comprehensive understanding of the overall behaviour of the building, leaving open the possibility to investigate also what was not initially expected [2]. The development of a common monitoring framework for calibration and validation of historical buildings' models remains a critical issue [44] and the creation of a standard entailing the most adequate indexes and variables for model calibration based on thresholds for climate variables (i.e., temperature and relative humidity) is urged [36].

For all the above reasons, it is crucial that researchers and practitioners approaching dynamic simulation of historical buildings possess a refined sensitivity and specific competence on the passive behaviour of historical buildings and are aware of the implications underlying the modelling assumptions formulated. Until the consolidation of an interdisciplinary approach for the application of dynamic simulation to the specificities of historical buildings, standardised procedures might hide energy and environmental behaviour anomalies due to historical, artistic, or constructive peculiarities [9]. The increase of studies published in this field would ideally contribute to finding useable assumptions and solutions for critical modelling issues based on previous experiences reported by researchers who faced similar problems.

### 4.4. Output

Simulation outputs were used both for the analysis of the current performance of historical buildings (*ex-ante* assessment) and for the design of renovation interventions for their energy and environmental improvement (*ex-post* assessment). The relevant number of reviewed case studies including relative humidity as an output that has been published since 2018 testified an increasing awareness of the not-negligible role of moisture exchanges for the study of the energy performance of historical buildings and for the assessment of climate-related conservation risks. Nevertheless, studies verifying the actual behaviour of historical buildings after the implementation of improvement interventions in relation to simulation results are still extremely sporadic [54], hindering the possibility to limit rebound effect and performance gap.

In the context of compliance with energy and thermal comfort requirements, it emerged the ambiguity of the current policy statements [107]. Although the EN 16883:2017 standard and the ASHRAE Guideline 34–2019 were specifically conceived to address the energy performance of historical buildings, their application has not become established in the field yet, likely due to a cumbersome translation of their general indications into operational practice [46]. On the other hand, standards on comfort requirements are still not adapted to historical buildings and inherent challenges remain to be solved [36]. As for heritage conservation, indoor climate monitoring and deterioration models for the simulation-based risk assessment of both movable and immovable artworks can be further explored in their integration with dynamic simulation.

## 5. Conclusions

Whole-building dynamic simulation offers a unique possibility to gain reliable insight into the performance of historical buildings, although their distinctive characteristics make it particularly challenging to adequately model their behaviour. Due to their inherent bundle of uncertainty related to inputs and model constraints, solid expertise and cautious calibration are required for the formulation of modelling assumptions and for the understanding of their implication on the energy and environmental representation of the buildings. Some valuable studies have already addressed specific operational difficulties by proposing a multiplicity of case-by-case modelling strategies, resulting in a limited comparability of the literature outputs. The use of simulations can be effective on the condition that users are aware of their intrinsic limits and leverage the expertise gathered by the scientific community, thus being able to identify priorities and filter out unnecessary steps. For this reason, further research is required to systematise modelling simplifications and to fully bridge the gap with the real complexity of historical buildings, which deals with an extremely heterogeneous matter and its evolution over time.

In this review, we broadened the discussion on the whole-building dynamic simulation of historical buildings through a systematic collection of case studies that were reported in the scientific literature up to 2022. Recurrent methodological issues and solutions were presented and discussed, together with a wide variety of current approaches, methods and processes proposed by researchers, highlighting critical insight into the pitfalls, workarounds, and crucial issues to investigate further. Notwithstanding the difficulty of deriving general patterns, it provided a useful basis to set solid ground for more informed and fit-for-purpose decisions, from input gathering to modelling strategies and output interpretation.

Historical buildings are ideal laboratories for refining the simulation process, as they generally entail interdisciplinarity, more complex analyses and tailored interventions. Despite the increase in the availability of modelling tools, whole-building dynamic simulations are still little exploited and are struggling to translate into professional practice for supporting evidence-based design. Although the issue of scarce capitalisation of dynamic simulation is magnified in the case of built heritage, the greater attention that our society places on the environmentally conscious conservation of historical buildings could provide an additional incentive in the application (and in the related investment of time and money) of more advanced simulation-based approaches for the decision-making support of energy and environmental improvement interventions, effectively promoting their diffusion in the construction sector.

The reviewed literature studies involved applications ranging from the simulation-based design to the multi-objective optimisation of energy savings, thermal comfort, and conservation requirements, up to the investigation of past and future scenarios on historical buildings. Data uncertainties and accessibility were found to be the main issues hindering a satisfactory translation of the complexity of historical buildings into dynamic simulation models; moreover, a critical approach to simulation is paramount to substantiate the heterogeneity of built heritage and to find effective workarounds to overcome the modelling abstractions and limited flexibility of software applications. General advisable practices in the definition of the input data were outlined, particularly about strategies for gathering suitable thermophysical properties of the envelope materials, for appropriately choosing weather data sources based on the research aims, and for a proper consideration of occupancy and HVAC systems. Similarly, recommendable solutions were pinpointed to support overcoming some typical constraints and limitations of simulation software tools in terms of both the geometrical and physical representation of historical buildings, especially when it comes to modelling their passive behaviour and hygrothermal exchanges. Further research is urged not only about calibration and validation procedures of the models, but also in terms of tailored comparative tests to verify differences among simulation software tools and algorithms.

The study highlighted that an extra effort is needed to entail a higher level of interdisciplinary dialogue among experts and the establishment and consolidation of a solid scientific community of reference to overcome the issues arising from the inhomogeneity intrinsic to the disciplinary field. Moreover, advanced competencies and a more sensitive approach towards the energy and environmental behaviour of historical buildings are urged to ensure a correct interpretation of the building's performance, since invasive and/or streamlined procedures conformed with new and existing buildings might be inapplicable and/or hide anomalies due to architectural and historical features as well as prompt maladaptation.

The whole-building dynamic simulation of historical buildings can finally be key to fostering the application of the newly released EPBD directive in the case of built heritage and to addressing the need for a harmonisation with the implementation of the recommendations included in the standard EN 16883:2017 for conservation-compatible energy and environmental improvement solutions. In this framework, regulating bodies would likely benefit more from requesting advanced methodologies of analysis, e.g., leveraging optimised workflows based on HBIM and tailored NDT campaigns, rather than stereotyped threshold results to be achieved. In addition, a smoother and more effective interoperability with other experimental and computational methods would advance the ongoing process towards standardisation in the field. Reinvigorating a fruitful interdisciplinary debate between experts through an increased number of scientific literature case studies and FAIR (findable, accessible, interoperable, and reusable) data repositories would greatly contribute to developing a critical mass of information and delivering a comprehensive and shared approach to the whole-building dynamic simulation of historical buildings.

## CRediT authorship contribution statement

**Elena Verticchio:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Letizia Martinelli:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Elena Gigliarelli:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Filippo Calcerano:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Conceptualization.

## Declaration of competing interest

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.

## Data availability

Data will be made available on request.

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