An Integrated Approach for Energy and Environmental Improvement of Built Heritage Through Building Information Modeling (BIM)

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1 Introduction

Energy consumption and climate change represent two of the main current international challenges and are an issue for built heritage as well, in terms of aggressive environments toward buildings, risk assessment from the macroscopic impacts of climate change and, due to higher energy cost, risk in terms of reduced usage of buildings, which is the most important factor to ensure their conservation. Historical buildings are not the most numerous nor energy-intensive portion of the building stock, thanks to their natural passive behavior optimized for their reference climate [1]; however, climate change is weakening this assumption with significant consequences for their energy consumption, the comfort of their occupants and conservation, thus urging the built heritage community to mobilize.

The concept of sustainable development as a basic principle of social action was introduced by the Brundtland report to the United Nations General Assembly in 1987 [2] and it was divided into three dimensions (economic, environmental and social), focusing on their balancing, in order to pass on a liveable world to the future generations. This initial approach evolved over the years thanks to the United Nations and the work of its Intergovernmental Panel on Climate Change (IPCC), aimed at providing the world with scientific information relevant to understanding the basis of the risk of climate change, its impacts and possible responses. The drafting of IPCC reports, since the first in 1990 [3] reviewed in 1992, [4], served as the basis for the United Nations Framework Convention on Climate Change and as a support for global agreements, among which the most important were:

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- The Rio declaration [5], that aimed at reducing greenhouse gas emissions without imposing mandatory limits, but nevertheless envisaging to hold successive conferences of parties (COP) to produce further and mandatory deeds.
- The COP3 Kyoto protocol, which introduced a legally binding treaty, committing signatory countries (representing initially about 18% of global emissions, AA. VV. [6]) to reduce emissions by an average of 5% compared to the 1990 levels in the period 2008–2012.
- the COP21 Paris agreement, a new global action to hold the global average temperature increase below 2 °C above pre-industrial levels and to increase the adaptation capability to climate change impacts, fostering climate resilience and reducing greenhouse gas emissions, also through economic support to these measures.

The concept of sustainability reached a milestone with the 2030 Agenda [7] and its 17 Sustainable Development Goals (SDGs), which, although unprecedented in scale and target achievement (eradicating poverty and achieving sustainable development by 2030 worldwide), provided a shared global vision and local applicability. This was achieved by taking into account both national realities and local context and challenges, including a strong follow-up mechanism [8] and defining a series of specific measurable and achievable objectives [7, 9]. In 2020, the European Commission also launched the New European Bauhaus, an initiative that emphasizes sustainability as a central element, and beauty and inclusion to rethink cities, making them more liveable, functional and accessible to all. Within this framework, cultural heritage represents a key asset for most of the 17 SDGs [10] and is being increasingly recognized as a fundamental driver for achieving its objectives [10–13]. One of the most advanced documents of this recognition is the Cultural Heritage Green Paper, developed by the most important stakeholders of the heritage sector reunited in the Climate Heritage Network, in response to the European Green Deal somewhat missing the mark on heritage [13]. The focus point of the document is that cultural heritage has a central role in the change envisioned by the EU Green Deal and should be considered more as a resource and less as an obstacle [14]. Among the most interesting statements, there is the potential of cultural heritage to involve citizens in the challenge of decarbonization and the professional upskill required for cultural heritage experts to take on the fight against climate change. More in detail, the chapter on historical buildings refers to the Renovation Wave [15], proposing built heritage as a driver to reach the objectives of the European Green Deal, with specific recommendations like: the principle of energy efficiency first; the revision of the Energy Performance Building Directive to include built heritage and the related approaches; the use of incentives to support the regulation, with specific mechanism for built heritage owners; the upskill of experts to support these interventions; the implementation of 100 demonstrators; the inclusion of the heritage sector within the high level forum of Architectural Engineering and Construction sector [14]; an attention to themes also shared by the EU Open Method of Coordination (OMC) group of Member States' experts on 'Strengthening cultural heritage resilience for climate change [13].

2 Toward a New Sensitivity in Built Heritage Conservation

The first step toward the new role of built heritage in the fight against climate change was achieved at a theoretical level through a process of disciplinary cross-fertilization between the conservation theory and the environmental design theory, of which the Italian scientific debate can show a bright example. Both disciplines are characterized by the need for a scientific approach to design, by an interdisciplinary point of view with holistic, multiscalar and systemic methodologies and by a time perspective that spans different generations [1]. However, their integration has not been smooth, also due to a delay in legislation (that we are still experiencing, by looking at the EPBD proposal of revision, EC [16]), especially when the economic pressure of the construction sector risks turn the issue of energy efficiency into a trojan horse for poorly controlled interventions on prestigious historic buildings. The seed for the switch toward a cross-fertilization of the two disciplines was identified by the scholar Giovanni Carbonara in the field of structural consolidation, where the historicization of the technical-technological operations, by putting them into a context of critical-technical reasoning [17] within the framework of critical restoration [18], allowed the development of a scientific approach. Although being less abstract and mathematical compared to the previously used methods to study ancient wall structures, this approach was not less rational or scientific, entailing a deeper comprehension of their functioning. Just as, for the consolidation of historical structures, the concept of improvement, as opposed to simple regulatory compliance, sparked a new era of good interventions, similarly, in the field of energy efficiency, the same principle has allowed to overcome the diffidence among experts and started an interdisciplinary dialogue that can support better interventions and offers at least four fundamental advantages to the scientific debate and technological application.

The first advantage is the interdisciplinary cross-fertilization in itself. Although the dialectical and interdisciplinary relationship between science, technology and restoration can be traced back at least to the Athens charter [19], the reductionist tendency to obtain an understanding of a complex object by studying its parts in isolation [20] constitutes a fundamental limitation in the field of restoration, in particular when a deterministically technical vision tends to overshadow more and more the critical historical contribution, up to the point of indirectly considering it useless. The reflection of the Scholar Liliana Grassi, however, suggests that cross-fertilization is not about defining a hierarchy of skills, but it is about giving theoretical formulation to the technological problem in the field of conservation [21]. This can be obtained by refusing a strong separation between cultural and technical aspects [21, 22], as demonstrated by the benefits that a critical perspective gave to the discipline, for example eliciting the criterion of homogeneity between the original static system and the intervention model, between ancient structures and modern additions, between traditional and innovative materials, ensuring greater compatibility and continuity of behavior to the entire building [23]. This reflection is extremely useful also in the environmental design field, as it can be considered like a compass for guiding the analysis every time the study of a building faces a knowledge problem that requires the use of field instruments or simulation methods, which struggle to work with the heterogeneity and complexity of the historical material. These are situations where a methodological compromise must be reached among procedures that, despite their limits, represent the best possible rational formulation of the knowledge problem on the basis of data, hypothesis and interpretation [24, 25].

The second advantage is the knowledge base for sustainability [13] provided by built heritage even for new construction, thanks to its awareness of the reference climate: a wealth of knowledge and methodologies that can also enrich the reasoning on built heritage conservation and decay phenomena (strongly affected, for example, by wind and sun exposure).

The third advantage comes from the emphasis that the EU directive 2010/31 [26] poses on the role of public administration as an example of the energy efficiency of the construction sector, and the role of historical buildings as symbols of European cities, if not of Europe itself, which confirms cultural heritage as a fundamental driver for its ability to involve citizens in the processes of ecological transition. This point of view is also stressed by the importance of promoting lighthouse demonstrator projects [13, 14].

The fourth advantage is the technological stress test that built heritage represents for environmental design methodologies. As demonstrated by several research projects [1, 27–30] but also by a few guidelines [31, 32], that tackled the issue from a much more operative point of view, the complexities related to those interventions makes built heritage the most demanding experimental laboratory ever to test new technologies and approaches and their scalability, and this requires also a continuous upskill of involved professionals and stakeholders [13, 14]. The maturation of this cross-fertilization process and of a new sensitivity among stakeholders on the energy and environmental improvement interventions of historic buildings is also supported by the integration of advanced digital technologies to support the whole process, namely Building Information Modeling (BIM) and Building Performance Simulation (BPS).

3 BPS and BIM Support to Energy and Environmental Improvement Intervention

BPS is among the most powerful tools to support the energy-efficient design of buildings. BPS is based on a behavioral model of a building at a given stage of its development, to study its energy and environmental performance from both comfort and energy consumption perspectives [33]. The main advantage of a simulation-based approach is to treat the building as an integrated system of optimizable elements instead of the sum of elements to be designed and optimized separately [34]. This provides decision support for environmentally and energy-efficient design solutions [35], producing relatively rapid feedback on the performance implications of the design hypotheses and allowing the exploration of design solutions, targeting performance objectives under economic constraints [36]. The use of advanced tools like dynamic BPS in particular is crucial for built heritage, as a simplified calculation method is not sufficiently reliable [13, 37]. BPS as a diagnostic tool falls within the Non Destructive Techniques group [1] and is therefore extremely useful when applied to built heritage, as it facilitates the understanding of complex phenomena by studying the relation between the building and the surrounding environment; in addition to supporting energy and environmental improvement interventions, it provides feedback on the evolution of decay phenomena and on the impacts of the intervention on them, and, lastly, it allows to investigate constructive events over the centuries in ways little explored so far (being able to understand how, back in the day, spaces and devices were used to ensure the comfort of occupants, thus providing further elements to the building analysis [25].

The other digital approach that is increasingly being applied to built heritage, because it provides a way to better address heterogeneity and accessibility of conservation processes, is BIM. The acronym BIM is generally used to mean Building Information Model and/or Modeling, referring to both the models created within BIM processes and the process itself; it is defined as the shared digital representation of a built asset that centralizes all the data (geometric and alphanumeric) on it [38, 39]. The BIM approach aims at organizing and managing all the phases of a building intervention, from its design phase up to construction and management. One of the main advantages of a BIM-based approach is the possibility to leverage the power of parametric modeling to increase the quality and flexibility of the model, which can be easily updated over time following the deepening of the analyses; this also reduces redundant operations and raises the accessibility of information that can be queried from the 3D model. The other advantage is the traceability and non-redundancy of the system, which has a positive effect on the velocity of the process (checks and corrections can be performed much more efficiently); lastly, the whole process benefits from this approach thanks to a clear definition of tasks and responsibilities and the enhancement of cooperative work [38]. BIM applied to built heritage is referred to as Heritage BIM (HBIM). HBIM application can also include a strong focus on documentation, thus providing a mean to keep track of all the information pertaining to the building, also if they span several centuries, of how new data was collected, how it was processed and interpreted and how the building changed or evolved after a conservation or energy and environmental improvement process [40].

Both BPS and BIM were developed for new construction and standardized buildings; therefore, transferring them to the built heritage is still an open issue. In both cases, the elaborated geometries involved, the heterogeneous materials and the difficulties in the characterization of structural, constructive and thermophysical properties determine a huge increase in modeling complexity. HBIM research started from mostly geometric-oriented studies [41] and then evolved toward interdisciplinary studies involving a wider array of other disciplines, ranging from historical and architectural analyses to diagnostics [42] and environmental design [25]. A series of increasingly structured references has been made available by sector associations, initially with a geometric focus [43], then also with an interest in the skills of the actors involved [44, 45] and in the BIM process in its entirety [46, 47]. BPS applications to historical buildings are also rising in number, with studies that are now focusing on the thermal representation of the geometry [48] and others that are trying to bridge the gap on other BPS-specific issues, such as the inertial behavior of wall masses, the importance of heat and air moisture transport, and of airflow between zones, infiltrations and the uncertainties related to the thermophysical characterization of the envelope [25, 49]. Moreover, although a simulation-based design process could be managed within a BIM approach, interoperability among the two environments is still lacking and in the development phase [50, 51], with very few cases on historical buildings [25].

4 The Integrated Approach of the Beep Project

The European Neighbourhood Policy launched the ENI CBC Med programme, aiming at bringing together coastal territories of the Mediterranean area to foster fair, equitable and sustainable development on both sides of the EU's external borders. Within ENI CBC Med priorities, the environmental protection and adaptation to climate change and mitigation stressed, in particular, the importance of supporting cost-effective and innovative renovations of public buildings within the specific climatic zone of the Mediterranean area. It is thanks to this programme that the BEEP (BIM for Energy Efficiency in the Public sector) project was able to address the whole process (shown in Fig. 1) of energy and environmental

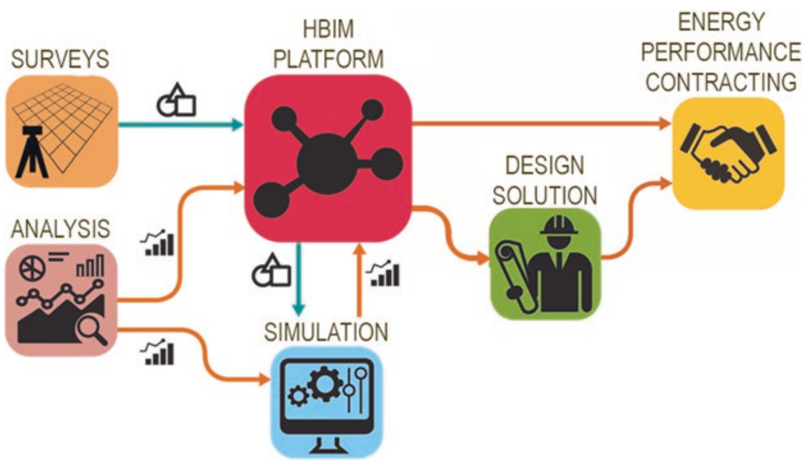

Fig. 1 BEEP process workflow highlighting data and geometry flows of the HBIM-based process

improvement of historical and public buildings and to effectively address climate challenges in the Mediterranean context (and its climatic specificities), thus requiring both a BIM and a dynamic simulation-based approach. The analysis phase was divided into historical and architectural analysis, geometric survey, conservation state analysis and energy and environmental analysis. The data were collected according to specific BIM templates to organize the information for their input in the BIM model and then to support an interoperability process toward the BPS, where the model was first calibrated and then used to foster the development of design interventions. The final outcome was then used as support for innovative financing mechanisms like the Energy Performance Contracting. Nine case studies in 7 different EU and non-EU countries (Italy, Spain, Cyprus, Lebanon, Egypt, Palestine and Jordan) tested the same workflow, that in the end produced a guideline that addresses each step of the process and focuses on its scalability to the professional practice [52].

5 Conclusion

The strong global pressure to evolve our Architectural, Engineering and Construction industry into an energy-efficient and sustainable sector, and the potential that built heritage has in this ambitious switch, is making the development and consolidation of new tools and methods to achieve this goal increasingly important; this is particularly true for historical buildings and their related complexities that generally require a higher skill compared to the rest of the building stock. This process, however, demands a solid theoretical framework to operate and a continuous study of these tools in order to make them scalable to professional practice, especially in the Mediterranean area where the climatic specificities call for a dynamic BPS approach. BEEP project had the merit to address the whole process and develop a guideline capable to guide the stakeholders through it, even in the highly specialized tasks, providing either support for executing the work first-hand or providing an alphabetization and support for outsourcing the tasks. This work will help future professionals and public-owned historical building managers to accelerate the transition toward an energy-efficient historical building stock, thus helping mitigate climate change and protect the buildings from its impacts and from the risk of abandonment.

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References

1. Gigliarelli, E., Calcerano, F., & Cessari, L. (2017). Heritage Bim, numerical simulation and decision support systems: An integrated approach for historical buildings retrofit. *Energy Procedia, 133*, 135–144. https://doi.org/10.1016/j.egypro.2017.09.379
2. WCED. (1987). *Report of the World Commission on Environment and Development (Brundtland commission)*.
3. Houghton, J. T., Jenkins, G. J., & Ephraums, J. J. (1990). *Climate Change The IPCC Scientific Assessment* [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_I_full_report.pdf
4. McG Tegart, W. J., & Sheldon, G. W. (1992). *Climate Change 1992 The supplementary report to the IPCC Impacts Assessment* [Online]. Available: https://www.ipcc.ch/site/assets/uploads/2018/03/ipcc_far_wg_I_full_report.pdf
5. UN. (1992). *United Nations framework convention on climate change* [Online]. Available: http://unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf
6. AA. VV. (2012). *Kyoto 1st commitment period (2008–12)*. https://ec.europa.eu/clima/policies/strategies/progress/kyoto_1_en
7. UN. (2015). *Transforming our world: The 2030 Agenda for sustainable development*. United Nations [Online]. Available: https://sustainabledevelopment.un.org/content/documents/21252030%20Agenda%20for%20Sustainable%20Development%20web.pdf
8. European Commission. (2015). *The 2030 Agenda for Sustainable Development and the SDGs*. https://ec.europa.eu/environment/sustainable-development/SDGs/index_en.htm
9. Allen, C., Metternicht, G., & Wiedmann, T. (2016). National pathways to the Sustainable Development Goals (SDGs): A comparative review of scenario modelling tools. *Environmental Science & Policy, 66*, 199–207. https://doi.org/10.1016/j.envsci.2016.09.008
10. Laine, A., Davies, J., Buchanan, K., Warren, K., & Turtinen, J. (2019). *Heritage Research Matters. Case studies of research impact contributing to sustainable development* [Online]. Available: http://jpi-ch.eu/wp-content/uploads/Heritage-Research-Matters.pdf
11. AA. VV. (2013). *The Hangzhou Declaration. Placing culture at the heart of sustainable development policies*.
12. H2020 Expert Group on Cultural Heritage. (2015). *Getting cultural heritage to work for Europe - Report of the Horizon 2020 Expert Group on Cultural Heritage*. Directorate-General for Research and Innovation.
13. Y. Directorate-General for Education. (2022). *Strengthening cultural heritage resilience for climate change: Where the European Green Deal meets cultural heritage*. LU: Publications Office of the European Union [Online]. Available: https://data.europa.eu/doi/10.2766/44688. Accessed 09 September 2022.
14. Potts, A. (2021). *European cultural heritage green paper*. Europa Nostra.
15. European Parliament. (2020). *A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives*. European Commission. https://ec.europa.eu/commission/presscorner/detail/en/fs_20_40
16. EC. (2021). *Proposal for a DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings (recast)*.
17. Carbonara, G. (2015). Energy efficiency as a protection tool. *Energy and Buildings, 95*, 9–12. https://doi.org/10.1016/j.enbuild.2014.12.052
18. Bonelli, R. (1959). *Architettura e Restauro*. Pozza.
19. VV. AA. (1932). *Athens Charter*.
20. Morin, E. (1990). *Introduction à la pensée complexe*.
21. Grassi, L. (1981). Problemi metodologici in relazione alla teoria del restauro. *Il Restauro Delle Costr. Muratura Probl. Metodol. E Tec. Consolidamento*, 9–11.
22. Pane, R. (1987). *Attualità e dialettica nel restauro*, edited by Mauro Civita. Chieti.
23. Carbonara, G. (1997). *Avvicinamento al Restauro. Teoria, storia, monumenti*. Napoli.

24. Croci, G. (2000). General methodology for the structural restoration of historic buildings: The cases of the Tower of Pisa and the Basilica of Assisi. *Journal of Cultural Heritage, 1*(1), 7–18. https://doi.org/10.1016/S1296-2074(99)00119-3
25. Gigliarelli, E., Calcerano, F., D'Uffizi, F., Di Biccari, C., Mangialardi, G., & Campari, M. (2019). *From Heritage BIM to BPS, a computational design-based interoperability approach*, presented at the BS2019, Rome.
26. EP. (2010). *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*.
27. (EURAC research) Troi, A., & Z. (Passive H. I. Bastian). (2014). *Energy efficiency solutions for historic buildings. A handbook*. Birkhäuser. https://doi.org/10.1515/9783038216506
28. Eriksson, P., Hermann, C., Hrabovszky-Horváth, S., & Rodwell, D. (2014). EFFESUS methodology for assessing the impacts of energy-related retrofit measures on heritage significance. *The Historic Environment: Policy & Practice, 5*(2), 132–149. https://doi.org/10.1179/1756750514Z.00000000054
29. Leissner, J., et al. (2015). Climate for Culture: Assessing the impact of climate change on the future indoor climate in historic buildings using simulations. *Heritage Science, 3*(1). https://doi.org/10.1186/s40494-015-0067-9
30. Webb, A. L. (2017). Energy retrofits in historic and traditional buildings: A review of problems and methods. *Renewable and Sustainable Energy Reviews, 77*, 748–759. https://doi.org/10.1016/j.rser.2017.01.145
31. V. AA. Energy Heritage. (2008). *A guide to improving energy efficiency in traditional and historic homes*. Changework resources for life [Online]. Available: http://www.changeworks.org.uk/resources/energy-heritage-a-guide-to-improving-energy-efficiency-in-traditional-and-historic-homes
32. MIBACT. (2015). *Linee di indirizzo per il miglioramento dell'efficienza energetica nel patrimonio culturale. Architettura, centri e nuclei storici ed urbani*. Ministero dei beni e delle attività culturali e del turismo Direzione generale Belle Arti e Paesaggio [Online]. Available: http://www.beap.beniculturali.it/opencms/multimedia/BASAE/documents/2015/10/27/1445954374955_Linee_indirizzo_miglioramento_efficienza_energetica_nel_patrimonio_culturale.pdf
33. Augenbroe, G. (Aug. 2002). Trends in building simulation. *Building and Environment, 37*(8–9), 891–902. https://doi.org/10.1016/S0360-1323(02)00041-0
34. Hensen, J. L. M. (2004). Towards more effective use of building performance simulation in design. In J. P. Leeuwen & H. J. P. Van Timmermans (Eds.), *7th International Conference on Design & Decision Support Systems in Architecture and Urban Planning, July 2–5*. Eindhoven University of Technology.
35. Hong, T., Chou, S. K., & Bong, T. Y. (2000). Building simulation: an overview of developments and information sources. *Building and Environment, 35*(4), 347–361. https://doi.org/10.1016/S0360-1323(99)00023-2
36. Clarke, J. A., & Hensen, J. L. M. (2015). Integrated building performance simulation: Progress, prospects and requirements. *Building and Environment, 91*, 294–306. https://doi.org/10.1016/j.buildenv.2015.04.002
37. Calzolari, M. (2016). *PRESTAZIONE ENERGETICA DELLE ARCHITETTURE STORICHE: SFIDE E SOLUZIONI Analisi dei metodi di calcolo per la definizione del comportamento energetico*. Franco Angeli.
38. ISO 19650. (2018). *ISO 19650:2018 Organization and digitization of information about buildings and civil engineering works, including building information modelling (BIM) — Information management using building information modelling —*.
39. National BIM. (2007). *Standard buildingSMARTalliance, National Building Information Modelling standard*. National Institute of Building Sciences.
40. Martinelli, L., Calcerano, F., & Gigliarelli, E. (May 2022). Methodology for an HBIM workflow focused on the representation of construction systems of built heritage. *Journal of Cultural Heritage, 55*, 277–289. https://doi.org/10.1016/j.culher.2022.03.016

41. Murphy, M. (2012). *Historic Building Information Modelling (HBIM). For recording and documenting classical architecture in Dublin from 1700 to 1830*, Ph.D. Dissertation. Department of Chivil, Structural & Environmental Engineering, Trinity College Dublin.
42. Bruno, S. (2018). *The implementation of automatic diagnostics and monitoring towards Diagnosis-Aided Historic Building Information Modelling and Management*, Ph.D. Thesis. Politecnico di Bari - DICATECh Department of Civil, Environmental, Land, Building Engineering and Chemistry.
43. Maxwell, I. (2014). *Integrating digital technologies in support of Historic Building Information modelling: BIM4Conservation (HBIM)*. COTAC. [Online]. Available: http://www.cotac.global/resources/COTAC-HBIM-Report-Final-A-21-April-2014-2-small.pdf
44. Maxwell, I. (2016). *COTAC BIM4C Integrating HBIM Framework Report Part 1: Conservation parameters*. COTAC [Online]. Available: http://www.cotac.global/resources/HBIM-Framework-Part-1-February-2016.pdf
45. Maxwell, I. (2016). *COTAC BIM4C integrating HBIM Framework Report Part 2: Conservation influences*. COTAC [Online]. Available: http://www.cotac.global/resources/HBIM-Framework-Part-2-February-2016.pdf
46. Antonopoulou, S., & Bryan, P. (2017). *BIM for heritage - Developing a historic building information model*. Historic England.
47. Historic England. (2019). *BIM for heritage: Developing the asset information model*. Historic England.
48. Akkurt, G. G., et al. (Feb. 2020). Dynamic thermal and hygrometric simulation of historical buildings: Critical factors and possible solutions. *Renewable and Sustainable Energy Reviews, 118*, 109509. https://doi.org/10.1016/j.rser.2019.109509
49. Widström, T., Bjrk, F., Gudmundsson, K., & Arfvidsson, J. (2019). *Simulation of historic buildings for enhancement of preservation and energy performance - issues and methods*. KTH Royal Institute of Technology.
50. Pinheiro, S., et al. (Jun. 2018). MVD based information exchange between BIM and building energy performance simulation. *Automation in Construction, 90*, 91–103. https://doi.org/10.1016/j.autcon.2018.02.009
51. Andriamamonjy, A., Saelens, D., & Klein, R. (2019). A combined scientometric and conventional literature review to grasp the entire BIM knowledge and its integration with energy simulation. *Journal of Building Engineering, 22*, 513–527. https://doi.org/10.1016/j.jobe.2018.12.021
52. Calcerano, F., Thravalou S., Martinelli L., Alexandrou K., Artopoulos G., & Gigliarelli E. (2023). *Energy and Environmental Improvement of Built Heritage: HBIM Simulation-Based Approach Applied to Nine Mediterranean Case-Studies*. Building Research & Information, May. https://doi.org/10.1080/09613218.2023.2204417