Integrated Numerical Analysis and Building Information Modeling for Cultural Heritage

Elena Gigliarelli – ITABC, CNR – elena.gigliarelli@itabc.cnr.it
Filippo Calcerano – ITABC, CNR – filippo.calcerano@itabc.cnr.it
Michele Calvano – Sapienza University of Rome – michele.calvano@uniroma1.it
Francesco Ruperto – Sapienza University of Rome – francesco.ruperto@uniroma1.it
Mario Sacco – Studio Arcrea, Rome – arch.mariosacco@gmail.com
Luciano Cessari – ITABC, CNR – luciano.cessari@itabc.cnr.it

Abstract

The use of numerical simulation applied to heritage buildings triggers a tremendous increase in complexity and at the present time, few studies focus on this issue and the problems of their calibrations. The difficulties are affected by many factors: the complex geometry involved, the non-standardization of building elements, the inertial behaviour of the wall masses, the importance of moisture transport; in short, the complexity of managing the design workflows in a conservation project of historical buildings. The integration of numerical simulation and Building Information Modeling is not yet automated and relies heavily on the manual steps and the individual experience. The research analyses the high potential of the use of the simulation of building performance, and the computational design along with Heritage Building Information Modeling, with the aim of pushing the three technologies to their potential limits, and promote their evolution towards an easier practical application. The paper presents an experimental HBIM workflow applied to a case study of a building located in an Italian historic centre and discusses a number of problems that still exist in the application of these workflows. They range from finding a correct set of information necessary for the analysis to the lack of interoperability that still exists between the software, up to the difficulties of the methodological approach. The results show that through a combination of recent open source software constantly evolving, it is possible to overcome some of the obstacles that prevent an effective interoperability between individual software, paving the way for an increasing number of useful solutions in the built heritage conservation.

1. Introduction

The construction industry in Europe is responsible for about 40 % of the total energy consumption and 36 % of CO2 emissions (Economidou et al. 2011; Berardi, 2015). The European Commission has undertaken several actions to reduce energy consumption in the building sector with two directives on the energy performance of buildings (EPBD 2002 and EPBD 2010 recast), but because of the difficulties in finding energy efficiency measures compatible with architectural, historical and cultural heritage values of the built environment, (also very vulnerable to climate change, Kilian et al. 2010) historical buildings have been excluded from these directives (European Parliament, 2012). However there is a large untapped potential in these interventions (Martínez-Molina et al. 2016; D'Ambrosio et al. 2015; Ascione et al. 2015), and in recent years, thanks to the adoption of the concept of energy efficiency as a tool to protect and support the conservative process, rather than a legislative restriction (Carbonara, 2015), the conflict between conservation practices and energy efficiency measures seems to be finally solved.

1.1 Building Performance Simulation and Built Heritage

Among the latest technical instruments to improve energy efficiency of the built heritage, building performance simulation (BPS) is one of the most promising. BPS is primarily a powerful tool for understanding complex phenomena (Clarke et al., 2015),

moreover it enables innovative applications in restoration design process and in non-destructive pre-diagnostics and diagnostics of cultural heritage. This depends also on its capability of providing feedback on energy and environmental implications of conservation interventions and on changes-embedded in the deterioration process. In spite of the possibilities of use offered by these tools, their applications are still few in the early stages of building design practice and even less in case of historic buildings, with a concentration of implementation examples in the Italian context (Ascione et al., 2015; Roberti et al., 2015; Cornaro et al., 2016). This is mainly due to the complexity inherent the historic building from a simulative point of view connected with the complex geometry involved, the lack of standardised building elements, the inertial behaviour of the wall masses, the importance of moisture transport, and not secondarily, the reluctant attitude of architects to use these tools in the design process (Paryudi, 2015). A major barrier to simulation tools in conservation design processes consists in fact in how to deal with a great amount and variety of information and with the complexity of architectural features (geometry representation, building envelope, survey of the passive behaviour, historical material characterisation, etc.) that must be taken into consideration with historic buildings.

1.2 The Heritage–BIM Approach and Interoperability with Building Performance Simulation

A historic building is characterized by a multitude of heterogeneous information that go beyond its physical and geometrical characteristics (Saygi et al., 2013). As demonstrated by a series of studies (Logothetis et al., 2015), the Building Information Modeling (BIM) technology seems capable of triggering a new evolution of an integrated and efficient management of the knowledge produced by the conservation process. In the field of Heritage Building Information Modeling (HBIM) after the first experiments on geometry representation (Murphy, 2012; Dore et al., 2015) the researches are gradually following other multidisciplinary studies based on interoperability with structural analysis (Oreni et al., 2014; Bassier et al., 2016), building operation and management (Barazzetti et al., 2016), documentation and design of restoration intervention (Gigliarelli et al., 2015) and environmental and energy retrofit (Gigliarelli et al., 2016). Since an HBIM model already contains a large amount of data required for a building simulation, interoperability can save time and costs while reducing errors and mismatches (Rahmani Asl et al., 2013). Unfortunately, the integration between BIM and simulation environments is still a complex issue, still in the development phase (Ivanova et al., 2015; Senave et al., 2015; Maile et al., 2013): the attempts of the BIM world to interact with the simulations have not yet produced satisfactory results. Using IFC format or gbXML certification it is still not possible to effectively transfer all the data needed for the simulation (Ahn et al., 2014), and often the BIM-based model for a BPS ends up so heavily influenced by the purpose of simulation to be of little use at an architectural level which results in a parallel modeling. On the other hand numerical simulations are still used as a combination of science and art based on the user's experience (Hitchcock et al., 2011), a non-standardized process that suffers the dichotomy between architecture and building a thermal vision (Wilkins et al., 2008). Information modelling, interoperability and knowledge management within the Heritage BIM become even more strategic within the legislative and regulatory framework that is being developed in various European countries also as a result of the European Directive 2014/24/EU on public procurement (European Parliament, 2014). With the Article 22 c.4 4. of the Directive 2014/24/EU "For public works contracts and design contests, Member States may require the use of specific electronic tools, such as of building information electronic modelling tools or similar" the legislator seems to guide all EU member states towards a BIM-based approach for public procurement even on historic buildings and highlights the need of a conscious adoption of methodologies and tools for building information modeling based on open standards for interoperable data.

2. Methodology

2.1 Proposed Approach, Needed Expertise, and Workflow

Given the current BIM-BPS interoperability limitations and additional complexities arising from the selected historical building, we opted for a semi-automated interface that is more reliable and suited to the task compared to a fully automated interface, thanks to its possibility of human intervention in the process (Ahn et al., 2014). The undertaken solution has exploited the computational design (CD) that is used today mainly for the generation of aesthetic form but has a huge untapped potential in performance-based design (Rahmani Asl et al., 2013) as an intermediate step between the two environments. Four specific experts were involved in the process: the conservation expert who followed the entire procedure from data collection up to the control of the results in terms of architectural HBIM and energy simulation, the BPS expert who contributed from the analytical phase through all the other steps to check the interoperability between the software, the BIM expert, and the CD expert. In conventional workflows geometry and building components modelling are executed in parallel between BIM and BPS, starting from a common multidisciplinary analysis (Fig. 1).

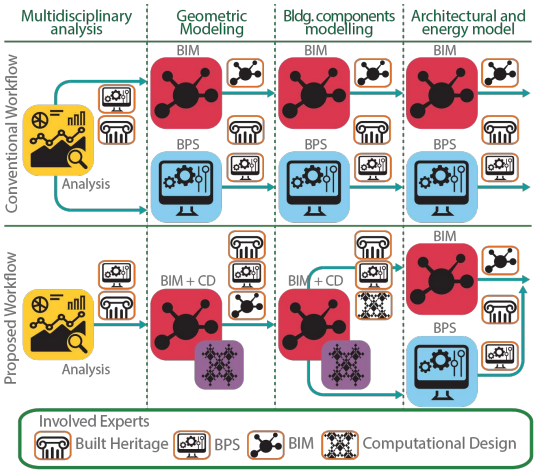

Fig. 1 – Conventional and proposed workflow to avoid parallel modeling and datasets

After a series of tests and experimentations, a new highly effective design workflow is presented, a process in which from the BIM software Archicad, the geometry is exported through gbXML schema, the opaque and transparent building elements through spreadsheets. Both data are then acquired inside the Rhinoceros-Grasshopper CD environment and then translated into an .idf file (EnergyPlus file format) through the two plug-ins of Grasshopper Ladybug and Honeybee (Roudsari et al., 2013).

The following workflow has been used (Fig. 2) to verify, under the coordination of the conservation expert, that the HBIM-generated information was correctly received by EnergyPlus:

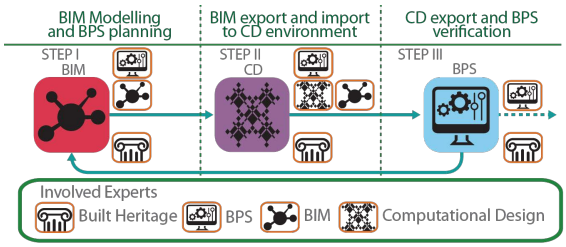

Fig. 2 – Testing workflow

- In the first step, HBIM modelling is performed while planning for the BPS the thermal zones or surfaces sub-division due to different boundary conditions or different building constructions;
- in the second step the model is exported from HBIM in a format that can be easily acquired inside the computational design environment where a first check of errors is carried out;
- in the third step, the .idf file is written by Honeybee inside the CD environment, it is then checked inside EnergyPlus Idf Editor and the simulation is launched. If the data transfer resulted inconsistencies, the process starts again from the first step.

2.2 Case Study

The case study, located in the historic centre of Frigento, is a traditional terraced house resulted by the merging of two previous units, and partly rebuilt after the earthquake in Irpinia in 1980. After conducting an in-depth historical analysis of its construction and evolution, a metric and geometric survey of its three-dimensional consistency was performed. The metric and geometric representation of the building was based on 3D laser scanner surveys and photogrammetry surveys with telescopic

3DEYE, compared with old drawings, archived documents, data concerning the historic construction techniques and architectural details, and enriched with in-situ direct specific measurements. The building walls are characterised by three different kinds of masonry (mainly Castelluccio limestone, with the exception of the North side which is in tuff, and part of the reconstructed east side that is in hollow bricks), with plaster on both sides. The windows are double-glazed, the floor is weakly insulated and ventilated with a crawl space: the first floor was rebuilt over the existing wood beams (retained) in reinforced concrete and hollow tiles with iron beams. The roofs were reconstructed in wood with weak insulation. Non-destructive diagnostic tests such as infrared thermography, magnetic analysis, and heat flux measures, were performed to determine thermo-physical characteristics and critical points. The energy request of the building was retraced through monthly energy bills.

2.3 Thermal Zoning and Energy Modelling

The first geometric interoperability tests were performed on very simplified models in a three-step process (Fig.3).

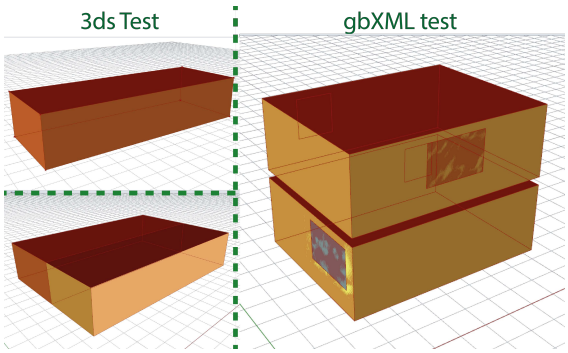

Fig. 3 – Geometric interoperability test models

First, the simple mass created by Archicad was exported in the .3dm file format of Rhinoceros, and then imported inside Rhinoceros to test the geometric functions of Honeybee (i.e. the transition from CD to BPS). Next a second simple volume was added in Archicad to verify surface matching of two adjacent surfaces for thermal zoning. In the third step a more complex geometry with walls thicknesses was modelled by Archicad and exported in .xml format through the gbXML schema. This allows the test of a zone creation, openings and surface matching separated by a gap corresponding to the thickness of the wall.

After these tests it was possible to address the specific complexities required by a thermal zoning and geometry representation of the heritage building, starting from the architectural model in HBIM. This approach simplified the design of the simulation and its thermal zoning because it allowed planning building simulation directly on an existing model. The building was divided into three thermal zones (ground floor, first floor, and north attic) in order to maintain the geometric representation of the masses only when it becomes crucial for the numerical representation (i.e. internal floors exposed to the sun). Therefore, some internal partition geometry was not exported into the energy model, since additional masses could be added later in EnergyPlus. Due to the massive characteristic of the building and to the great differences between walls, the HBIM-based energy model preserved all the existing thickness differences. This solution generated two problems on the model: the first was the creation of additional and not required surfaces in the automated generation of Archicad spaces (every time walls of different thicknesses were present on a coplanar surface). This barrier was eliminated by setting the construction of the walls on the internal axis in Archicad before exporting the file through the gbXML schema. The manual intervention highlighted the need for a better automation of the space construction, capable to bypass a heritage building typical problem that occurs when thermal zones are different from the spaces defined by real internal partitions.

To solve the second problem, linked to the thermal zoning as well, the boundary condition for the Archicad spaces was removed from two internal partitions. Then in Archicad two virtual surfaces were modelled in parallel (Fig.4, last model, green areas) with space boundary properties in order to replace spaces as needed for thermal zoning. It is recommended a better space modification ability in Archicad to reduce the geometric issues arising from the thermal zoning.

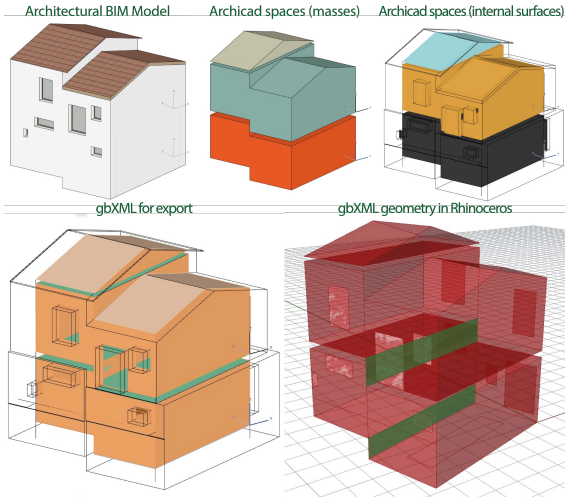

Fig. 4 – Generation of the thermal model from the BIM environment

Geometric modelling was completed by adding the geometry of the surrounding buildings as shading surfaces for the simulation (Fig. 5). The reconstruction resulting from a laser scanner survey of the historic centre of Frigento was acquired and modelled in HBIM, transferred to Grasshopper and then to EnergyPlus.

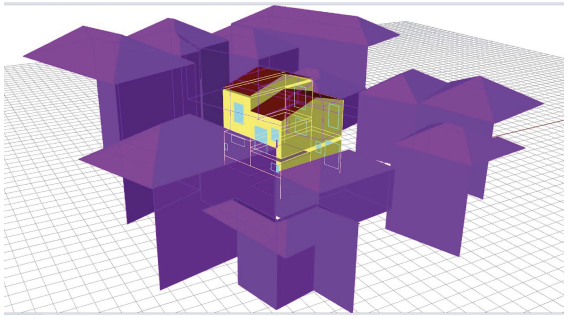

Fig. 5 – Geometry representation inside the Rhinoceros environment of the thermal zones and the context surfaces imported from the BIM model

2.4 Building Components Modelling

Building materials and construction elements were specified in Archicad and then acquired through spreadsheets generated by the software. The main problem to address in terms of compatibility concerns the different ways by which Archicad and EnergyPlus manage materials and construction elements. Firstly, in an Archicad environment the building material is defined by the thermo physical properties and the thickness is set up when creating the construction element (composites), while in an EnergyPlus environment the same material with different thicknesses has a different value and a different name. Secondly, the materials stratigraphic sequence of some composites in Archicad is the inverse of the one required by the EnergyPlus construction elements (i.e. roofs). The solution of both problems was found in the CD environment where, once acquired from Archicad, materials were automatically duplicated and renamed according to their thickness value as required by EnergyPlus. For the construction elements the problem was solved by defining an additional value for each Archicad composites elements to be exported in the spreadsheet. This value was used to clearly indicate when and in which thermal zone a stratigraphy needed to be duplicated and reversed.

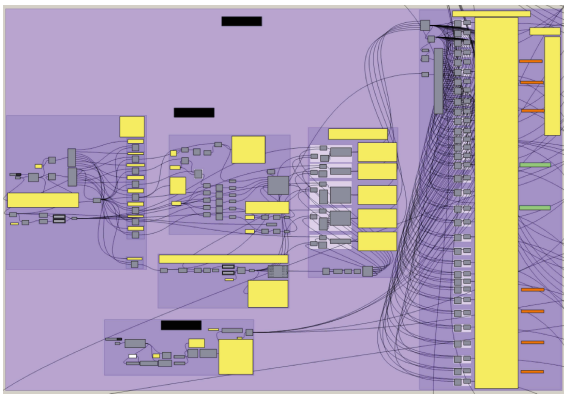

Fig. 6 – Grasshopper screenshot of the data acquisition for building materials and construction elements

These steps were needed to keep the HBIM model simple and as less as possible affected by modification generated for the simulation purpose.
Although at the end of the process all the issues were addressed, the process required complex computational design software architecture (Fig. 6), this shows that a greater automation of the translation process inside the BIM environment is highly desirable.

2.5 EnergyPlus file check and simulation

In the final Grasshopper file (Fig. 7), the geometry and the building elements were manually matched inside the corresponding thermal zone, along with the rest of the input for the simulation through Honeybee. The generated .idf file and the error files of the simulation were then checked, they resulted in no errors.

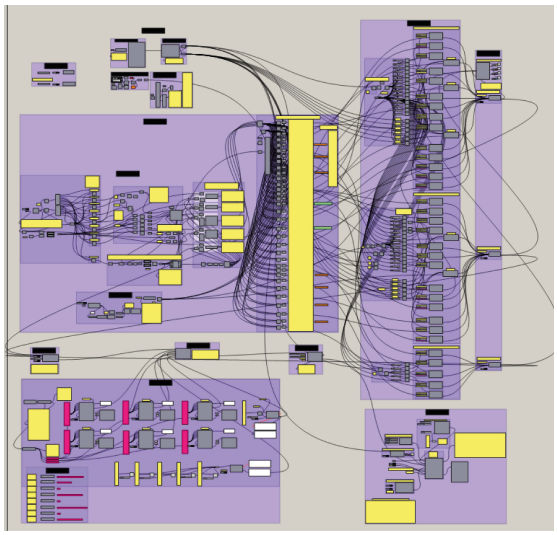

Fig. 7 – Grasshopper screenshot of the final Grasshopper file that links together Archicad and EnergyPlus

3. Results and Discussion

A new fully implemented methodology to link together Heritage-BIM and BPS is proposed that, through an integrated approach involving the joint work of a multidisciplinary team of experts (in conservation of architectural heritage, building performance simulation, building information modeling and computational design) in conjunction with the use of a set of up-to-date open source software is able to generate and modify geometry and building elements both for the thermal and the BIM model through an active and parametric link. The semi-automatic approach increases the speed by which reliable simulations can be produced and allows the team to intervene directly in all data transfers. There are still interoperability limits between the two software environments, that could be overcome through future research and tests by the team. However, its development represents a significant step towards the production of tools combining the parametric design process with performance analysis.

3.1 Future Research

Future research developments will aim to simplify and improve the proposed workflow that integrates the BIM with numerical simulations, reducing non-automated steps to limit the risk of errors and mismatch, while preserving the possibility of human intervention, a crucial need raised by the conservation field. Additional possibilities for data exchange (i.e. schedules and internal gains) between the two environments will be further investigated along with the data visualisation of the simulation results inside the HBIM environment.

Acknowledgement

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Nomenclature

Acronyms

BPS	Building Performance Simulation
BIM	Building Information Modeling
HBIM	Heritage Building Information Modeling
CD	Computational Design

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