From Heritage BIM to BPS, a computational design-based interoperability approach

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Abstract

The article deals with the fundamental issue of the interoperability between BIM and BPS in the complex context of historic buildings conservation. As the current tools for the transition from BIM to BPS follow a black-box approach in which it is difficult for the experts to intervene efficiently without doing several parallel operations, this paper proposes a semi-automatic approach that uses Computational Design (CD) to manage the data flow between the two environments. This allowed an interdisciplinary team of BIM, BPS, CD and conservation experts greater control on the scientific coherence of the single operations involved in the process.

Introduction

Preserving the built heritage and reducing energy consumption are two important issues though coordinated actions at the level of European directives and regulations are still missing (Mazzarella, 2015). This is due to two peculiar characteristics of historical buildings: the complexity of dealing with historical-aesthetic aspects in interventions and better energy performance compared to the majority of the highly energy-consuming buildings (Economidou et al., 2011, Pretelli and Fabbri, 2016; Martinez-Molina et al. 2016) executed between the Second World War and the introduction of the first energy efficiency regulations (Fabbri, 2013). Nevertheless, improving the energy efficiency of historical buildings lowers the generally high management costs (AA, 2008) thus facilitating their occupancy or re-use, which is fundamental to guarantee their good conservation (Carbonara, 2017). Over the last few years, conservation theory has finally started to recognise energy efficiency as a strategy to protect cultural heritage (Carbonara, 2015). The most interesting threads in this field (Saygi et al., 2013) are the Heritage Building Information Modeling (HBIM), for the digital management of the knowledge produced during the conservation process, and Building Performance Simulations (BPS) as an instrument to better understand and predict the evolution of decay phenomena (Lång et al., 2018) including compatibility, sustainability and energy efficiency of the interventions on the built heritage.

BPS and Built Heritage

BPS can be ascribed to the category of non-destructive analysis and thus they are particularly interesting tools to support the conservation process of historical buildings. However, despite the potential benefits deriving from their integration in the analysis and the design workflow, their use is still not widespread noting that the majority of case studies is located in Italy (Ascione et al., 2015; Cornaro, Puggioni, and Strollo 2016; Dalla Mora et al., 2015; Tronchin and Fabbri, 2017; Cellura et al., 2017; Castaldo et al., 2015; Aste et al., 2016). This depends on the typical and higher complexities of historical buildings, that make the simulation harder to calibrate (Roberti, Oberegger, and Gasparella, 2015; Permetti, Prada, and Baggio, 2013; Kramer, van Schijndel, and Schellen, 2013). These complexities are mainly related to:

- uncertainties in measuring the (physical and thermophysical) characteristics of the envelope;
- irregular and complex geometry as opposed to still-basic digital energy models, which fail to correctly represent the relations between the surfaces;
- the lack of standardised or homogeneous construction elements. The modelling task can be very challenging: from the extreme case of a complex facade with a multitude of historical phases and consequent different stratigraphies, to the simpler case of the inhomogeneity of a single wall (Roberti, Oberegger, and Gasparella, 2015), which could be deteriorated or damaged in some parts with consequent differences in thermophysical properties along its surface;
- the inertial behaviour of the masses. Beyond a certain thickness, the limitations of current BPS software applications require specific measures and cautions (Mazzarella and Pasini, 2017);
- the importance of moisture transfer and the complexities related to its calculation (Paolini et al., 2016).

Heritage BIM and BPS interoperability

BIM is a methodology for the design, representation, production and management of the built environment, mainly applied to new constructions. Its application to historical buildings (HBIM) represents a targeted answer to the growing demand for methods in management and accessibility to multidisciplinary knowledge (Fai et al., 2011), and it is progressively expanding from applications in the geomatics field (Pocobelli et al., 2018) to multidisciplinary experimentations (Maietti et al., 2018) even in the energy efficiency field (Logothetis, Delinasio, and Stylianidis, 2015; Gigliarelli, Calcerano, and Cessari, 2017; Miller et al., 2014). BIM models already contain most of the necessary information to
create simulative thermal models. Linking the two environments could therefore improve the whole analysis process (Pinheiro et al., 2016). However, data transfer between the two software environments is still inefficient: studies are in ongoing development (Bazjanac, 2011; Senave and Boeykens, 2015; Maile et al., 2013; Hijazi, Kensek, and Konis, 2015; GSA, 2012; Kamel and Memari, 2019) and no strong evidence yet suggest that these workflows are diffused in the current professional practice (Calquin, 2017). Interoperability problems concern data re-input, lack of data exchange between the two environments, errors in the geometry transfer and loss of active parametric link between the environments (Lam et al., 2012; Pinheiro et al., 2016). Data transfer mainly occurs through two open file formats, the Industry Foundation Classes (IFC) standard, a data model designed for vendor-neutral exchange of digital building models, and the Green Building Extensible Markup Language (gbXML), a specific file format for BIM to BPS interoperability (Miller et al., 2014; Hijazi, Kensek, and Konis, 2015; Lam et al., 2012; Pinheiro et al., 2016; Dong et al., 2007). Again, even using these two file formats it is still not possible to efficiently transfer all the needed data (Ahn et al., 2014) and moreover, there is little control on the process (Miller et al., 2014; Cemesova, Hopfe, and Mcleod, 2015; Dimitriou et al., 2016). The issues can be traced back to the different logic with which the two software environments evolved (Hijazi, Kensek, and Konis, 2015), and to the difficulty of BPS software in exploiting the advantages offered by BIM object oriented programming (Jeong et al., 2014). It should also be considered that numerical simulations are still the result of a combination of science and art based on the user experience (Hitchcock and Wong, 2011): a process still little standardized (Guruz, Katranuschkov, and Scherer, 2016) that suffers from the rift between design and energy modelling (Wilkins and Kiviniemi, 2008). This forces the BIM model to be simplified for BPS, resulting in the loss of information links among the different actors/disciplines (meaning the loss of one of the main benefits of BIM).

Methodology

This research follows a previous study (Gigliarelli et al., 2017) on interoperability between BIM and BEP that used Graphisoft Archicad as BIM software and EnergyPlus as energy modelling software. This time Autodesk Revit was tested as the starting BIM platform for the process. The first step was designing a workflow for HBIM and BPS integration to be applied on a real case study. Given the current limitations of automatic workflows (that still require a strong manual intervention by specialists but tend to exclude them), a semi-automatic approach was chosen (Ahn et al., 2014) taking advantage of Computational Design (CD) and web-based open source tools to manage the data flow between the two environments. Four disciplines with related experts were integrated into the process: the conservation and simulation experts followed the whole process from the development of multidisciplinary analyses to the case study characterization up to the energy model construction and checking. The BIM experts were involved in the HBIM modelling of the building and in the data flow planning and development along with the CD expert. The main goal was the conservation of the highest level of freedom and consistency in every expert’s specific workflow while keeping the parametric link active between BIM and energy modelling. A series of team meetings allowed the experts to share their operational processes, requirements and desires in order to develop a common understanding of the whole process. After highlighting similarities and differences between the two environments and the major issues (described later), we jointly planned a mapping system and a complete data flow in order to bridge the gaps, anticipate and find solutions to all known problems. Thus the data flow was articulated in an iterative workflow of modelling and testing, organised in five main steps (Figure 1):

1. HBIM architectural and thermal modelling (Autodesk Revit) including materials thermophysical properties. We mapped the output of the modelling phase, intended as geometric spaces and properties, as input value for the following steps. We added specific “interoperability driven” parameters” (a set of properties introduced first in Revit as custom parameters) and then exported as variables of the same type (text strings, integers etc.) to be used as input in the following steps, as required by the data flow plan.
2. exporting (both geometry and data) from the HBIM model through the most suitable path to the CD environment (Rhinoceros/Grasshopper);
3. first checking of the exported file in terms of transferred geometry and data (using the web-based Aragog gbXML Viewer and a CD environment);
4. energy modelling (through Ladybug and Honeybee Grasshopper’s plugin) from the acquired data, creation of the simulation .idf file, simulation run;
5. last checking for the correct data transfer within the CD environment up to the previously created .idf file, with a return to step 1 in case of errors.

Case study

The building object of the study (Figure 2) is located in the historic centre of Frigento in the Campania region (IT), a city hit by the 1980 Irpinia earthquake, and it is the result of the merging of two previous terraced buildings located at different levels and the partial rebuilding of the first floor. We performed a historical-typological
architectural analysis, a geometric survey with traditional and innovative techniques (3D Laser scanner and photogrammetric surveys) followed by an energy audit using non-destructive instrumental measurements (heat flux meters, infrared thermography, magnetic analyses) for the construction elements and thermo-physical properties characterization. The analyses highlighted three types of masonry plastered on both sides with a prevalence of Castelluccio Limestone, Frigento local stone. The north side masonry is in Tuff, the first floor east walls were rebuilt in hollow bricks. Almost every masonry in the building has its own different thickness, and the walls on the west side are partly below ground at different heights. The windows are double-glazed, the ground floor slab is weakly insulated on the north side with a crawlspace, while the first floor slabs were rebuilt over the existing wooden beams as slabs in hollow core bricks and iron beams. Both sloped roofs were rebuilt in wood, the southern one has skylights and is weakly insulated, the northern one covers an uninsulated attic and is not insulated.

Case study generic and specific modelling problems

Some differences in the internal logic between Revit and Energy+ complicated the data flow from the beginning. Balancing the two environments requires a joint planning upstream of the data flow to maintain the disciplinary workflow needs of the two software ecologies. A common data transferring problem is the different logic used by Revit and Energy+ to define the thickness of the building materials. While in Revit different thicknesses can be associated to each material (such as the case of the Castelluccio Limestone masonry various thicknesses), Energy+ requires a new material (with its specific name) for each variation of thickness. Another general problem lies in the order in which Revit and Energy+ organise the different material layers within a building envelope stratigraphy. Revit materials are stored within the building components from top to bottom for the horizontal surfaces and from the outside to the inside for the walls. Energy+ has instead a unique rule for all the construction elements, from the inside to the outside of the related thermal zone. This issue requires specific inversions of the material layer position when transferring data from BIM to Energy+ for almost all the envelope building components, excluding the horizontal lower surfaces of the thermal zones (for example the ground floors). Consequently, both orders need to be preserved to solve the surfaces adjacency matching in case of shared surfaces between adjacent thermal zones. Another quite common problem is the lack of biunivocal correspondence between a single Revit instance (a wall for example) and the surfaces of the thermal zones in Energy+. In architectural BIM modelling a single wall instance can span through different levels but its translation through the thermal modelling must be divided into multiple surfaces (at least one for each thermal zone). The historical case study adds further specific geometric problems. The first lies in the Energy+ boundary condition that require (in addition to the exact surface matching between adjacent thermal zones at different heights) a further increase of the Energy+ surfaces starting from individual instances in Revit (e.g. in the external west walls, which are partly below ground at different heights). Another problem is related to small differences in height and thickness of single walls that create additional surfaces of connection between the individual thermal zones.

First exporting tests and modelling problems

The first exporting tests started from a system of linked HBIM models in Revit (the building file into the context model obtained by a laser scanner survey of the whole historical centre) using the gbXML format. Through the thermal zoning based on the two connected terraced buildings, we modelled all the relevant massive surfaces for the solar gains (the only exception was the partition wall between the north and south parts of the building that was nevertheless modelled to separate the two parts of the house). The final model has 5 thermal zones (North and South ground floor, North and South first floor and North attic, Figure 7). To obtain 5 thermal zones the “room bounding” property was removed within Revit from nearly all the internal partition walls, however a first problem emerged. The architectural zoning (room) and thermal zoning (space) in Revit follow the same logic/editing tools and even if it is possible to divide a room into more than one space, it is not possible to merge multiple rooms into one space, an aspect that greatly limits the art of a targeted energy modelling and that irremediably affects the workflow of one of the two disciplines at the expense of the other. The room/space editing tools are few and insufficient for a correct energy modelling, even if jointly used with the few tuning parameters available: both the “room bounding” property, that can be activated on walls still considering all the hosted doors or windows, and the room/space separation lines, that do not include the openings, work only in a plan view and cannot be edited in a section view, except for the height. The first gbXML export tests (evaluated with the web-based open source software Aragog gbXML Viewer) did not produce acceptable results with both exporting methods provided by Revit. In both cases the poor flexibility in the modelling tools did not guarantee the necessary control on the process. With the "energy settings" export mode we encountered most of the problems, as shown in Figure 3.1: key surfaces were
totally skipped during the export, other surfaces were subdivided in several others, it was not possible to merge internal zones into single ones and while running several tests from simple to complex geometries (trying to simplify the exporting geometry to obtain better results) it was also hard to find a pattern in the export logic. The “use room/space volumes” setting for export mode offered instead greater control over the process (still presenting the overlapping problem related to the logic for architectural rooms and thermal spaces). However, new issues arose in the form of additional surfaces on simple geometries (in fewer and less complex, but still relevant quantities): additional shading surfaces, wrong boundary conditions and additional surfaces between thermal zones when a single façade includes different thicknesses (Figure 3.2).

The attempt to solve this problem by tuning the modelling of Revit spaces to be exported as thermal zones has however clashed with the above-mentioned rigidity of modelling tools for these elements. The automatic recognition of the spaces in Revit created adjacent thermal zones (North and South Ground Floor and North and South First Floor) that due to differences in wall thicknesses did not have the east and west sides on the same axis, as shown on Figure 4.

We tried to use room/space separation lines to slightly tune the model and avoid these misalignments, but this action generated other problems, as the room/space separation lines did not recognise the hosted openings (doors and windows). Furthermore, if the separation line went beyond the core axis of the wall, the relationship between wall and floor went missing thus generating an additional “L shaped” geometry as shown in Figure 5. All these issues after several tests on the gbXML files imported into Aragog gbXML Viewer (in a loop between step 1 and step 3 of the abovementioned workflow) led us to abandon in this experimentation the gbXML file format (that instead was used in the past experiment with Graphisoft Archicad).

Figure 3: Example of export results with Revit “energy” and “use room/space volumes” settings, with issues on added shading surfaces, boundary conditions and additional surfaces (Aragog gbXML Viewer 12.34).

Figure 4: Western surfaces misalignment of the thermal zones on the ground floor (Ground Floor South - green line and Ground Floor North - red line).

Figure 5: “L shaped” added geometry as a result of the use of room/space separation line to tune the model and avoid surface misalignments on east and west façades.

Geometric modelling and data flow

Therefore, we opted for a way that is even more manually controllable by the multidisciplinary team. The geometric modelling of the five thermal zones started from an assembly of three nested BIM models, where the architectural model linked within its context served as a basis for the thermal model. This third BIM linked file was developed through a manual modelling using conceptual masses for the thermal zones, ready to be exported in the CD environment, as shown on Figure 6.

Figure 6: HBIM schema and thermal zoning.

Ensuring the evidence of design changes across the models/teams through the copy-monitor tool, it was also possible to keep active the link between the geometry of the thermal model and its architectural counterpart by connecting specific reference levels and axis. This way, the basic structure of the thermal model, appropriately simplified compared to the architectural model in terms of thermal zoning and alignments, was developed. The Revit file contains five “boxes” made of conceptual masses and several curves for openings and other energy modelling specific needs as for example some separation lines needed to obtain two surfaces with two different boundary conditions from the same Revit instance. The geometry was then exported into a .dwg file as ACIS solids and acquired in the Rhinoceros-Grasshopper environment ready to be exploded and reassembled for energy modelling through an algorithm developed with the open source environmental Grasshopper plugins Ladybug and Honeybee (Roudsari and Pak, 2013), the latter a graphical user interface for Energy+ based on a very flexible toolbox approach. Within the first part of the algorithm we slightly modified the imported Boundary
Representations (BREPs) by dividing certain surfaces for
the energy modelling. In the second step, we intersected
the BREPs between each other using the Honeybee_IntersectMasses component to perfectly match
the surfaces of the thermal zones and achieve the redundancies required by Energy+. This was a
particularly important step in our case where the thermal
zones are positioned at different heights and needed
further subdivisions on the shared surfaces. In the third
step, we reconstructed the system of heights and child-
surfaces (openings) that composes each individual
thermal zone. We plugged in each surface the material and
stratigraphic data from the BIM architectural model
(acquired as explained in the following paragraph), and
we inputted the special boundary conditions manually.
We then merged the five thermal zones within a further
automatic passage carried out by the Honeybee_SolveAdjancencies component, which solves
all the relationships between adjacent surfaces of different
thermal zones. Finally, we added the geometry of the
context to take into account the shading of the neighbouring buildings, plugging it directly into one of
Honeybee's final components for writing the .idf file and
launching the simulation (Figure 7).

Figure 7: Geometry construction algorithm developed
with Honeybee within the Rhinoceros / Grasshopper
environment and energy model geometry.

Materials and building components modelling and
data flow
Due to the difficulty of having the same model for the
architectural and thermal building analysis, a customized
workflow was implemented to map additional parameters
in Revit and easily match the architectural components
and the built-in conceptual masses (corresponding to each
thermal zone). Materials, surface names, inversion
parameters were associated from Revit to the correspondent CD surface in order to keep the relation
between the models coherent. First, the thermal masses
were extracted from the architectural domain, then the
graphy was translated from the masses to the CD
environment. Finally, all the relevant properties were
reconstructed from the architectural model to the CD
environment. This produced new “interoperability-
driven” parameters required by the thermal modelling
during the HBIM modelling in the BIM environment: the
internal and external surface roughness of the materials;
the name of the future thermal model surface on the BIM
instance (required to monitor the data flow because some
instances of Revit are linked to two or more surfaces in
the thermal model); the "composite inversion" parameter
necessary for the management of the above-mentioned
layer order discrepancy between Revit and Energy+.
Using Revit APIs, it was possible to develop a C# script
to extract and save data into an Excel spreadsheet. The
code was useful to solve minor discrepancies between the
output values and the input data required in Grasshopper,
such as different measurements units. Once we acquired
the spreadsheet in Grasshopper, we exploded the data and
reassembled it to build up, through Honeybee’s
components, first the Energy+ materials and then the
Energy+ construction according to an ordered data flow
that required three main steps. In the first step, we created
different material for each different thickness related to the
same Revit material. A single Plaster, whit a thickness
of 02 and 04 cm in Revit, became now a couple of
materials with two different names in Energy+, Plaster02
and Plaster04. Once all the materials were created with
Honeybee’s specific components, we reconstructed the
stratigraphies in the Honeybee_EPCOnstruction component according to the following rule triggered by the
"composite inversion" parameter: with a value of 0 the stratigraphy was maintained as it came out from Revit and
rebuilt for Energy+; with a value of 1 the stratigraphy was reversed (and its straight counterpart was discarded), with
a value of 2 both the straight and inverted stratigraphy
were created and stored for Energy+ (i.e. as needed for the
walls between two thermal zones). In the final step, we
created a list of all the Energy+ Construction elements
required by the thermal model starting from Revit data
and then we connected all the Energy+ Construction to
their specific surface as shown in Figure 8.

Simulation check
Finally, we enriched the thermal model with schedules
and simulation parameters, through other specific
components of Honeybee up to the creation of the .idf file
and its simulation that (in the last iteration of the process)
resulted in no errors.

Results and discussion
Results of the workflow tested on a case study of a
terraced historic house with afio in Irpinia (Italy) show a
high potential for the reduction of parallel geometric and
semantic modelling to meet the requirements of the
simulation software. The data flow must be designed
before the process takes place by an interdisciplinary team
capable to anticipate and model the needs of the
simulation software during the HBIM modelling. The
data takes the form of custom and specific interoperability-driven BIM parameters that are extracted from the BIM model and re-assembled for the simulation software through an intermediate step in a Computational Design environment. The workflow created a system of models that followed their internal work logics, without forcing neither the models themselves nor the specialists out of their typical approach. The process combined these models into a federated set in which the parametric link remained active and in which any subsequent modifications (typical of an in-progress restorative diagnostic process) did not cause particular input problems thanks to the possibilities offered by the parametric environment.

**Conclusion**

The debate on using deterministic tools and approaches on heterogeneous buildings with high levels of uncertainties can be traced back to the historical dialectic between hard and humanistic sciences in the restoration field. Energy improvement of built heritage should follow the path of other disciplinary fields (such as structural diagnosis, Croci, 2000) where a methodological compromise was reached between procedures that are not strictly analytically demonstrable, but represent to date the best possible rational formulation of the problem on the basis of data, hypothesis and interpretation (and are therefore to be included within the knowledge process). The complexities and irregularities of historical buildings increase the level of unforeseen problems that need to be addressed promptly, through a direct joint intervention of the expert team. The decision to test the transition from BIM to BPS on a historic building (with atypical problems compared to the totality of similar studies) allowed us to highlight a series of rigidities and limitations inherent to the process, unresolved issues in both geometric and data modelling and specific needs of the built heritage industry (a sector poorly represented in this type of studies). This will help to further develop the application of HBIM and BPS on interventions related to historical buildings, where both performance-based design and data management are issues of absolute relevance and necessity. A highly flexible semi-automatic approach allowed us to overcome the problems and proved to be an even more crucial need in the conservation field: the interoperability workflows, although increasingly automated, should always guarantee the possibility of human intervention during the various steps. This approach also had the advantage (within the CD environment) of a continuous control over all the features associated with the geometry and data flow through specific components of Honeybee and Grasshopper dedicated to display and check various parameters. The energy model as it is being built can thus be displayed through specific queries for different types of surfaces (roofing, walls, openings...), boundary conditions, associated building construction etc. Other checks can be performed on the specific geometric characteristics of the surfaces (convex or non-convex) or on the thermal zones (closed or open BREPs). The reasoning that led to the development of the "interoperability-driven" parameters that have become necessary for our workflow could also be used to elaborate specific control parameters for other studies that focus on the automated workflows in order to increase flexibility and fine-tuning possibilities of the process. Compared to the previous workflow that used Graphisoft Archicad, in this case it was not possible to use the export to gbXML feature of the BIM software, having to start again from a conceptual mass export into .dwg file format with consequent loss of data and the need for little additional geometric modelling in the Rhinoceros-Grasshopper environment. The data flow related to the thermo-physical properties of the materials and building components was instead smoother thanks to the scripting step in Revit that simplified the matching between the measurement units and the conventions of the two environments. Also, the internal logic of the "composite inversion" parameter was improved. The share of manual intervention in the workflow (prone to error) is still too high to be able to consider this process as mature, even in a relatively simple case study as the one we tackled.

**Future Developments**

The future developments of the research will focus on addressing in greater detail the limitations emerged in the IFC and gbXML export/acquisition phases, and on tuning the algorithm in order to reduce manual steps, limit errors and speed up the construction of BPS starting from BIM. A version of Ladybug and Honeybee is currently under development also for Autodesk Dynamo BIM which could allow tackling the whole workflow within Revit itself excluding the need of an export towards Rhinoceros and thus simplifying the workflow. Further research can also be carried out to check IFC Energy configuration views in its 4th release and in the upcoming 5th release. However even if in the future the current modelling and export limitations will be solved by more effective automatic approaches, the built heritage industry will probably always need the possibility to manually intervene on the process when necessary.

**References**


