SCIRES it
SCIentific RESearch and Information Technology
Ricerca Scientifica e Tecnologie dell'Informazione
Vol 15, Issue 1 (2025), 85-96
e-ISSN 2239-4303, DOI 10.2423/i22394303v15n1p85

CASPUR-CIBER Publishing, http://www.sciresit.it

VISUAL PROGRAMMING LANGUAGE TO SUPPORT INTEROPERABILITY OF GEOMETRIC AND DATA MODELLING IN HBIM PROCESSES

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Abstract

HBIM is widely used as a management system to support documentation, conservation and enhancement of historical buildings. However, multidisciplinary activities often require the integration of different software environments to support tailored geometric alphanumeric data representation and to keep all experts within their digital tools of choice, but interoperability is still challenging. This study proposed a digital workflow, based on a Visual Programming script, to seamlessly integrate the use of CAD programs for modelling complex shapes and the use of spreadsheets for data manipulation with BIM tools, within a unified information management system, applied to historical buildings and floor constructions. It confirms the complementarity of different data modelling methods and demonstrates the effectiveness of Visual Programming in supporting the digitisation and management of built heritage.

Keywords

HBIM, interoperability, VPL, built heritage, modelling

1. *Introduction*

Heritage Building Information Modelling (HBIM) is gaining traction to support the documentation, conservation and enhancement of historical buildings (Bastem & Cekmis, 2022). BIM is defined as the digital representation of the physical and functional characteristics of a building (buildingSMARTalliance, 2007; ISO, 2018); when applied to heritage, it constitutes an information management system able to integrate and structure heterogeneous geometric and semantic data (historical, diagnostic, etc.), ensuring their permanence, consistency and implementation by a multidisciplinary team of experts (Gargaro, Giudice, & Ruffino, 2019). To this end, an HBIM model must be carefully planned, establishing model uses and subsequent model strategies.

As BIM is mainly a methodology for information management, there is no fixed software application for its implementation; however, most of the so-called 'BIM authoring tools' available on the market are object-oriented modelling systems. The building, and its model, are divided into constructive components corresponding to 3D objects; these objects are structured into classes and defined according to a set of parameters relating to their geometric and semantic characteristics, often in the form of key-value pairs (Eastman, Teicholz, Sacks, & Lee, 2018). The hierarchical relationship of an object to those associated with it is called 'behaviour', and it simulates the behaviour of the corresponding constructive component. Following the breakdown structure of the building into objects to be modelled, a Level of Information Need should be established for each object, describing the information to be implemented in its quality, quantity and granularity (CEN, 2020). This 'simulative' and semantic approach is different from the 'metaphorical' approach of CAD (computer-aided design) 3D software application, where geometric shapes are given an architectural meaning by convention (e.g., a parallelepiped identified as a wall by the modeller), and allow for a robust data framework (Angulo-Fornos & Castellano-Román, 2020).

However, as most BIM authoring tools have been developed to depict industrialised construction, the rules and relationships governing BIM models can hinder the representation of complex and heterogeneous geometries and information, which are typical of historical buildings (Valentini, Battini, & Vecchiattini, 2023). These intrinsic characteristics frequently necessitate a degree of flexibility in modelling that is not always adequately addressed by BIM tools, resulting in difficulties in accurately reproducing the irregular aspect, ornamental details and structural peculiarities of built heritage. This is particularly evident in the treatment of curved surfaces, ornamentation and sculptural elements, which compromises the fidelity of the model and its informative value.

The use of CAD programs is a more suitable alternative for manipulating complex shapes with greater freedom. However, they can exhibit deficiencies in representing information. In fact, while BIM tools emphasise the management of data to facilitate the construction and maintenance of buildings, CAD programs tend to prioritise the manipulation and graphic modelling of shapes.

The interoperability between CAD and BIM tools is described by Angulo-Fornos & Castellano-Román (2020), who propose an overview of BIM modelling methodologies, also including CAD geometric modelling and export to BIM. Biagini et al. (2016) applied different strategies to model the architectural elements of the SS. Nome di Maria church in Italy, including the creation of the geometry of the vaults in Autodesk Autocad, to be imported into Autodesk Revit and used as bases for surface models. The Basilica of Collemaggio, damaged by L'Aquila earthquake in 2009, was modelled with McNeel Rhinoceros and Bentley Pointools, to allow for an accurate representation of irregularities, and then exported to Autodesk Revit for semantic enrichment (Banfi, 2016; Oreni et al., 2014). The HBIM model of the St. John the Theologian Cathedral in Nicosia (Cyprus), carried out in Autodesk Revit, involved the external modelling and import of the cross vault, presenting a strong deformation (Santagati et al., 2021).

As most of these examples show, the integration of CAD objects into BIM tools is still challenging because the imported geometries often present limited possibilities of geometric and information manipulation compared to native objects.

In the context of information management related to historical buildings, a large amount of data on documentation, analysis and conservation activities can come from different sources or is produced by a multidisciplinary team of experts, many of whom are not familiar with BIM methodology. For instance, typological, technical and architectural classification and description of constructive components are often developed by conservation experts through spreadsheets or databases, in tabular format. The manual integration of this information within BIM models, as well as its update, can be wearisome and prone to errors, redundancies and inconsistencies, rendering the synchronic or diachronic work of different experts on the same element unfeasible.

Therefore, the semantic enrichment of BIM models requires adapting the objects generated by BIM tools to a multiplicity of information contexts with specific data parameterisation, to make them consistent and meaningful within these contexts. The process involves the definition of new keys for BIM parameters, followed by careful assignment and configuration within the BIM model. Moreover, there is a need to develop automatic or semiautomatic interoperability workflows between BIM and other data management environments to import/export and synchronise key definitions and values' insertion, to maintain consistency in data structure and content.

The use of visual programming language (VPL) has been tested to solve the issue of modelling complex shapes and to establish interoperability workflows (Calvano, Martinelli, Calcerano, & Gigliarelli, 2022). VPL allows for the definition of programming scripts through the development of visual graphics, which operate with text, graphical symbols and arrows, rather than textually. It enables the interoperability of CAD and BIM processes, facilitating the interconnection of a multitude of external applications with the BIM tool used. This interlinkage between diverse tools allows for the transfer of knowledge pertaining to the historical built environment, thereby enriching the model with valuable insights.

The implementation of this type of automated methodology presents a multitude of advantages, including enhanced consistency and robustness in the semantic enrichment of objects, a reduction in processing time, and a streamlining of repetitive and tedious tasks, thereby reducing the possibility of error. Moreover, it enables the comprehensive exploitation of digital technology to enhance the efficiency of information management operations in the domain of built heritage.

Lanzara et al. (2024) investigated open-source VPL scripts to manage and compare diagnostic multi-sensor data, which can be geolocated and annotated by conservation experts, also validating the interoperability between different information systems (e.g. BIM/HBIM, EM, graphic engines).

Regarding geometrical shapes, Giovannini developed different VPL solutions to face the 3D modelling challenges posed by historical construction elements in a BIM environment, depending on the input data (Giovannini, 2023). The use of parametric adaptive families (classes) of objects in Revit was compared with the development of scripts using the Revit VPL Dynamo, to automate the modelling of different types of vaults of Urbino Ducal Palace. VPL, more flexible and able to generate complex geometries, presented challenges in replicating the relationships (behaviour) of different model objects (Quattrini, Sacco, Angelis, & Battini, 2023). Roman et al. (2023) introduced a semi-automated approach to model the complex shapes of architectural elements using Dynamo and a Boundary-Representation method (B-rep), based on point clouds, with a Scan-to-BIM approach.

Within a conservation process, the Revit model of the Jewel Tower in London was integrated with alphanumeric moisture data, organised in spreadsheets and linked via parametric objects representing the measurement points, while the spatial distribution of moisture was depicted using Dynamo (Pocobelli, Boehm, Bryan, Still, & Grau-Bové, 2018). Barontini et al. (2022) implemented a strategy to report and monitor damage evolution over time, tested on the Ducal Palace in Guimarães, Portugal: it includes a spreadsheet to be filled in by inspectors, whose results are included in a Common Data Environment and uploaded in the BIM model. Dynamo was also used to integrate alphanumeric inspection data on functions, conservation state and maintenance, recorded in Excel spreadsheets, within the BIM model of the Florio former tuna factory in Favignana, Italy, to accommodate a wide and complex range of information into a single centralised digital system (Bernabei et al., 2023).

Rule-based routines written in a VPL script in Dynamo were developed to analyse the visual strength grading of timber structural elements, within an HBIM methodology for data management, applied to the Town Theatre of Noicattaro in the province of Bari. Data were organised in homogeneously codified databases, supporting the automated assessment of residual performances (Bruno & Fino, 2021).

Lo Turco et al. (2022) tested different semi-automatic HBIM-VPL workflows to manage conservation and enhancement activities in museums, linking the container (building) with its content (collections); the most relevant for the current study investigated the association of information from the Facility Report to individual BIM objects, to predict and monitor the conditions of museums' collections.

The state of the art highlights the variety of current approaches to VPL, for both the geometric modelling of complex shapes and data integration. However, these types of applications still require advanced technical skills in the use of VPL and BIM tools and in understanding the specific requirements of the information context in question. Moreover, the use of VPL to enhance interoperability among the software applications used by different actors of the built heritage sector is still lacking within HBIM processes, limiting their potential to support a comprehensive information management of historical buildings. The development of tailored VPL codes, to solve common interoperability issues, would support geometric modelling and data integration and support interdisciplinarity, favouring the combined work of experts versed in different tools.

From this point of view, the current study proposes an approach to interoperability, based on VPL, which couples the use of CAD programs for modelling complex shapes and the use of spreadsheets for data manipulation with BIM tools, within a unified information management system. The selection of a specific VPL solution, bridging various data structures, allows for mapping and controlling distinct digital processes within the same environment, enhancing a consistent and robust workflow. The synergy that results from this interoperability allows the peculiarities of each tool to be exploited, thereby ensuring an accurate and informative representation of built heritage.

2. *Materials and methods*

2.1 Case study description

The proposed approach was applied to the documentation, conservation and restoration of historical buildings, and in particular to floor constructions. The case study is the *Sala della piattaia* (or *Sala dell'Ares Ludovisi*), with a peculiar wooden *Senese* slab structure and brick flooring, on the noble storey (first storey) of Palazzo Altemps, located in the proximity of Piazza Navona in Campo Marzio in Rome, which stands as a prominent example of Renaissance and Baroque architecture. Palazzo Altemps is currently part of the National Roman Museum, and it is dedicated to the history of art collecting, housing classical sculpture collections such as the Boncompagni-Ludovisi and Mattei collections.

It was built in the 15th century at the behest of the Florentine Girolamo Riario, lord of Imola and Forlì and nephew of Pope Sixtus IV. In 1511, it was purchased by Cardinal Francesco Soderini and renovated by the architects Antonio da Sangallo the Elder and Baldassarre Peruzzi, who designed the main courtyard. It was bought in 1568 by the cardinal Marco Sittico Altemps, who undertook extensive renovations and expansions and placed here his collection of antiquities and library. During the Baroque period, the palace was a cultural and political centre; over the centuries, the Altemps family's fortunes waned, and the palace changed hands multiple times until it was sold to the Holy See at the end of the 19th century, to be used as a seminary by the Pontifical Spanish College. In 1982, it was acquired by the Italian State and, after restorations, partially opened as a museum in 1997. Following the acquisition and restoration of the whole building, it was completely opened in 2006 (Bertoldi & Giovanetti, 2000; Scoppola, Maresca Compagna, & Vimercati Sanseverino, 1987).

The *Sala della piattaia* on the noble storey is part of the oldest nucleus of the palace (Fig. 1), under the ownership of the Riario family. It was selected for the typological singularity of its floor construction in the context of Roman Renaissance, which makes it a remarkable architectural element to document, and also because it has similar characteristics to the other floor constructions, so its modelled behaviour can be extended to the whole building.

The Department of Architecture of Roma3 University (DArc), within the INT4CT project

Fig. 1: Sala della Piattaia in Palazzo Altemps, Rome.

coordinated by Professor Pugliano, developed a typological scheduling of the floor construction, based on their previous work on a thesaurus for the typological description of historical buildings and building elements, to implement the regulation and catalogue of architectures of the Central Institute for Cataloguing and Documentation of the Italian Ministry of Culture. Starting from chronological information, it allows one to document almost every aspect of a building, with an in-depth study of its technical components, aimed at describing the construction techniques used and the state of conservation, to support conservation and restoration activities (Pugliano, 2009).

Within the analysis of floor construction, the scheduling and integrated thesaurus, developed as an Excel spreadsheet, can describe the technological and constructive characteristics, damages and decay patterns, and in-depth examination of wooden components (Aveta, 2014). It is divided into two levels, reported in different tabs: SO (*strutture di orizzontamento*), which refers to the floor as a whole, and SOE (*strutture di orizzontamento – elementi*), which describes the typological components, as well as the single elements, constituting the floors.

The DArc group also provided a photogrammetric survey of the *Sala della piattaia*, integrated with the plan of the noble floor, derived from Scoppola et al. (1987) and the survey of the room (Bertoldi & Giovanetti, 2000).

2.2 Tools used

The approach proposed involves a set of software applications:

- McNeel Rhinoceros 7: 3D CAD freeform surface modeller that utilises the NURBS (Non-Uniform Rational B-Splines Modeling) mathematical model, suitable for complex geometries. It can support customised processes and is equipped with a robust Visual Programming Language (Grasshopper) for automation of procedures and connection between software applications in different domains (https://www.rhino3d.com/)
- Bumblebee 2: plug-in for Grasshopper to read and write data to Excel spreadsheets (https://github.com/interopxyz/Bumblebee)
- Autodesk Revit 2023: Building Information Modelling software, more and more used in applications of HBIM
- Rhino.Inside.Revit: plug-in to integrate Rhinoceros (CAD) and Grasshopper (VPL) in the Autodesk Revit environment, by querying, modifying, analysing, and creating native Revit elements within Grasshopper (https://www.rhino3d.com/inside/revit/1.0/)
- Microsoft Excel: spreadsheet editor to analyse and manipulate data.

The data produced during the research were structured in a Common Data Environment (CDE), a digital repository for storage, sharing and management, allowing information to be tracked, reviewed and verified.

3. Results

3.1 Applied workflow

The study encompassed the development, via VPL, of an interoperable parametric CAD-BIM model of the *Sala della piattaia* in Palazzo Altemps using Revit and Rhinoceros software applications; the model was semantically enriched with data from the existing typological spreadsheets, through a semiautomatic connection between Excel and Revit.

The aim was to define a workflow to integrate, in a BIM federated model, geometrical and alphanumerical information from heterogeneous sources (surveys, documentation, CAD models), to implement a centralised source of information, continuously updated, while taking advantage of the suitability and potential of different software applications. Moreover, this approach fosters interdisciplinarity by supporting the collaboration of various experts (modellers, surveyors, restoration and conservation experts, etc.), even without specific knowledge of BIM, whose workflow of choice is flawlessly incorporated into the methodology without disruptions. In fact, the use of the plugin Rhino.Inside.Revit allows for the seamless integration and management of software applications and digital processes in a unified environment. The interoperability of BIM with a CAD modeller (for shape modelling) and a spreadsheet editor (for alphanumeric data manipulation), given their respective advantages in terms of data representation, familiarity of use, and adherence with model uses, allowed us to make the most of the peculiarities of each tool, ensuring an accurate and informative representation of historical architectural components.

An essential step in digital modelling is the analysis of the geometric and technical characteristics of the architecture to be represented. The workflow envisaged the breakdown structure of the room and its construction floor into model objects, following the typological spreadsheet provided by DArc and adapting it to the hierarchical organisation of Revit.

The software arranges objects into classes, called ‘families’, which describe building elements with common characteristics, belonging to the same construction category. Families are further divided into types, which specify the values of given parameters of the family; a single object, part of a family and type, is called an ‘instance’. This organisation closely adheres to the existing typological description in the spreadsheet, based on a thesaurus for cataloguing historical buildings and elements. In implementing the spreadsheet for the proposed workflow, special care was dedicated to distinguishing information at the type level (technological and constructive characteristics) from information at the instance level (production, installation, damages and decay patterns), to enhance interoperability.

The 3D point cloud from the photogrammetric survey was used for the Scan-to-BIM modelling of complex geometries in the CAD software Rhinoceros, as a “scaffold” upon which objects are modelled. Through the use of VPL, the modelled objects were imported into Revit as parametric families, controlled by geometric, topological and formal rules; therefore, they retained the flexibility to be modified according to the conditions of the specific context and, if feasible, applied to similar cases, with the necessary modifications.

VPL was also used for the semantic enrichment of the model objects, by importing the information provided by the spreadsheet: the data structure was integrated in the model as parameters’ keys, while the data content as parameters’ values, both at the type and instance level. This operation is diachronic and biunivocal: modifications in the values of the model objects can be transferred automatically in the spreadsheet and vice versa, enhancing consistency.

3.2 Geometric interoperability

As the BIM functionality for handling complex shapes is limited, the 3D CAD software Rhinoceros was used for modelling, and then the objects were imported into Autodesk Revit.

The direct import of CAD models into BIM environments generally produces static objects that lack parametricity, making both geometric and information modifications difficult; to achieve an effective integration, great attention was paid to the export process, in order for the model to retain the highest possible degree of flexibility and adaptability to BIM's parametric criteria.

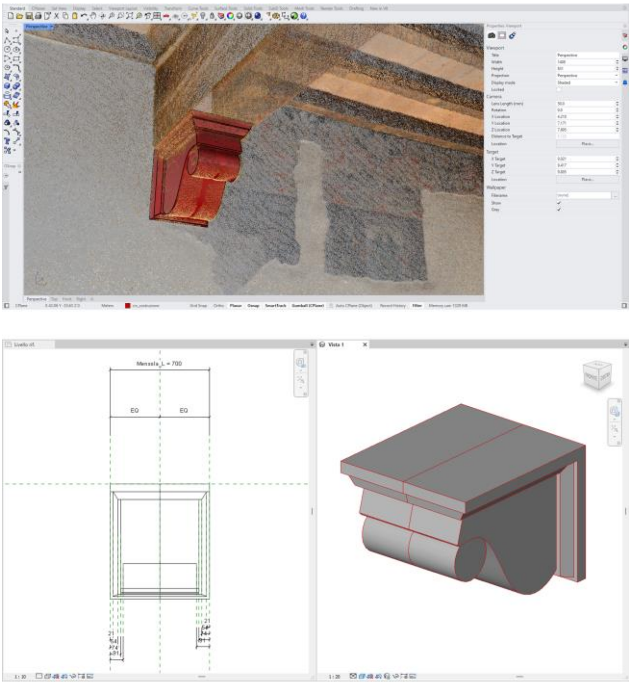

Fig. 2: Comparison between the beam support modelled in Rhinoceros and exported as a parametric, fully modifiable family in Revit.

Processing of the geometric model began with the segmentation of the point cloud into recognisable architectural elements. The segments were then imported into CAD for reverse modelling, which transforms the discrete representation of the cloud into a continuous model based on NURBS surfaces.

To ensure consistent modelling, an appropriate level of discretisation was adopted, using simple geometric operations such as extrusion, translation along a path and rotation.

In addition, the complexity of the surfaces was regulated, avoiding an excessive number of control points or cutting operations that could have compromised the flexibility of the model.

A crucial aspect of interoperability between CAD and BIM environments is the transfer of objects without loss of morphological information, such as geometric representation and topological structure. The use of standard exchange formats would have resulted in the loss of certain fundamental properties. To overcome this limitation, an approach based on VPL and Rhino.Inside.Revit technology was adopted, allowing the smooth data export between the two environments. This method guarantees the native transfer of elements, preserving constraints and geometric properties, maintaining the parametric nature of the objects and ensuring their modifiability within the BIM environment.

As an example, Fig. 2 shows the modelling of the beam support in Rhinoceros and exporting to Revit. The level of detail adopted made it possible to obtain a 3D model by means of extrusion of generating curves along a directrix line for two of the three main elements. The vertical and horizontal tables, located between the wall and the beam respectively, were modelled by modifying parallelepipeds. In the extrusion process, the directrix line was maintained at the first degree to ensure geometric consistency.

The VPL script controlled not only the parametric model of the element in Rhinoceros, but also allowed for its direct export/import as a family object in the beam category in Revit,

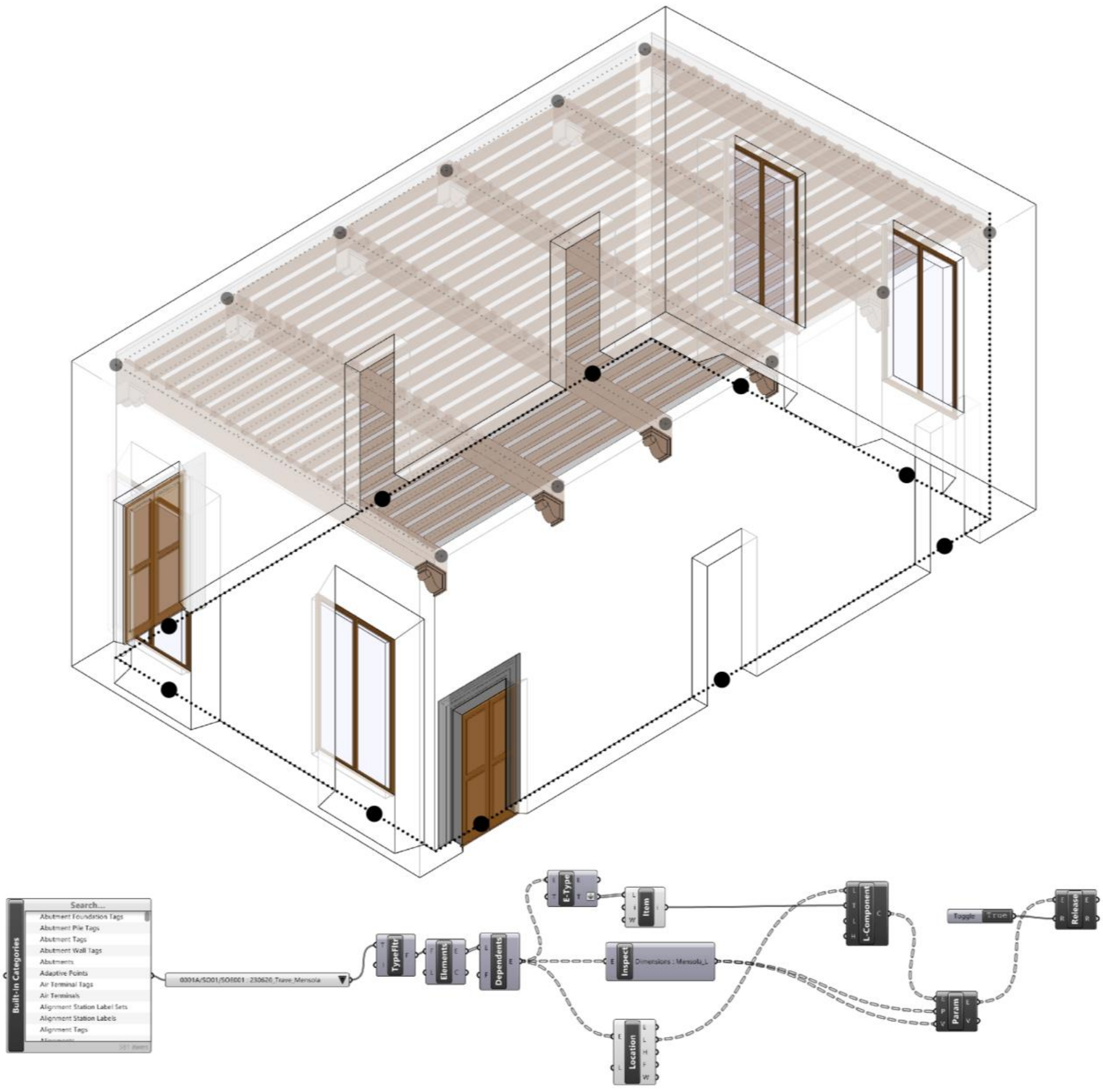

Fig. 3: Schematic representation of the HBIM model as a result of the VPL script, underlining the geometrical tracing and the distribution of the architectural elements. The extract of the script shows the positioning of the main beams.

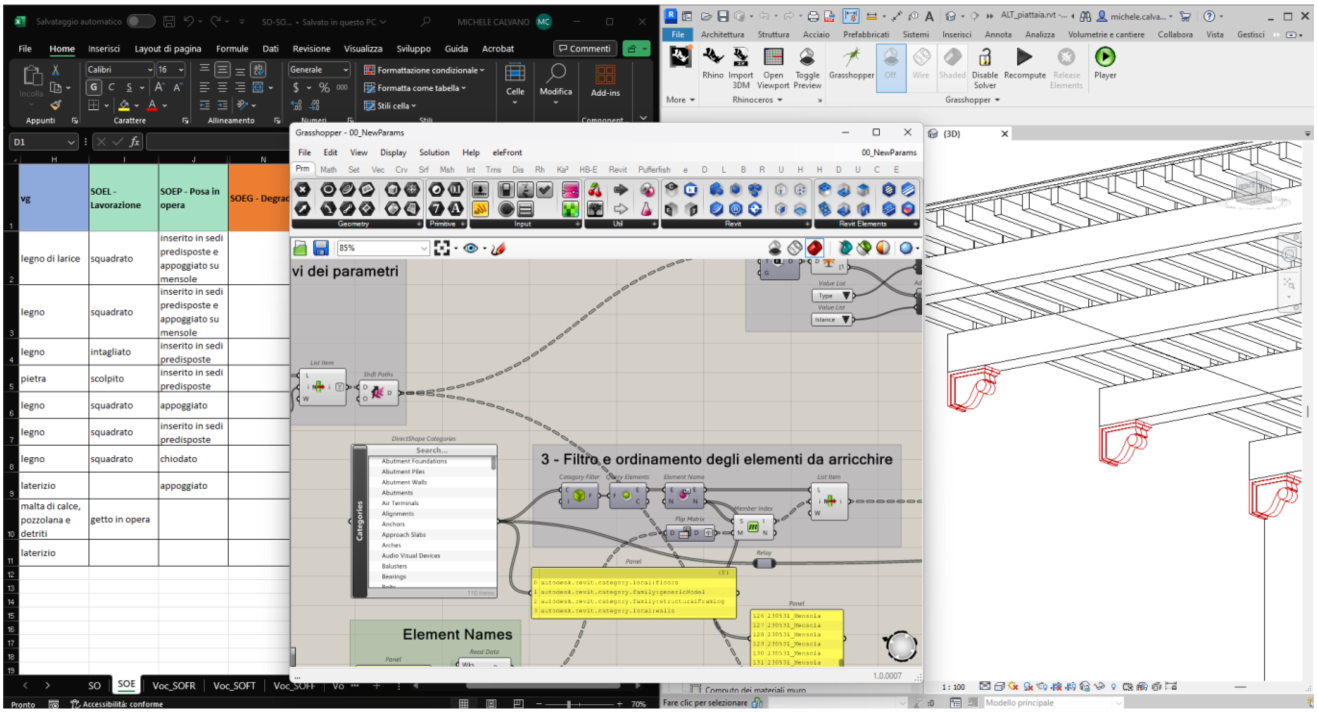

Fig. 4: Overall interoperability between Excel and Revit via Rhino.Inside.Revit

maintaining its geometrical adaptability, and the assignment of geometric constraints and variable numerical parameters within the BIM environment. The result is a robust parametric family, controlled by dimension constraints, equivalent to a native object.

VPL was also used for the integration of the single building elements within the BIM model, based on the definition of their underpinning geometrical tracing, to formalise the algorithmic process of architectural composition, expanding on the workflow developed in (Calvano, Calcerano, Martinelli, & Gigliarelli, 2023).

The walls were modelled by outlining their geometrical path (internal finish line, height) on the point cloud and mapping and selecting the corresponding wall type. The other components of the floor construction, such as main beams, secondary beams, decking and slab, were modelled with the VPL script by developing Revit families and distributing them parametrically in relation to the floor outlining, which was acquired from the walls' path. The windows and doors, modelled as loadable families, were placed by identifying their insertion points in the point cloud, in reference to the walls' path. Each element was assigned to the appropriate construction category, taking full advantage of BIM's parametric capabilities.

Fig. 3 schematically shows the modelling process of the room and its components within the Rhino.Inside.Revit script, with an extract of the script to position the main beams.

3.3 Semantic interoperability

The semantic enrichment of model objects was implemented with another VPL script in Rhino.Inside.Revit, by linking the typological spreadsheets and BIM model (Fig. 4).

Considering the content of the spreadsheet from the point of view of the BIM model, the rows of the spreadsheet represent either model instances (i.e., single objects), or model families and types, that are classes and subclasses in Revit; the columns refer to keys of attributes (written in the first row), and the cells express the value of the parameter indicated by the column/key for the given row/instance or type.

Type and instance parameters are identified in Excel by using different cell fill colours for the first row. The connection between the spreadsheet and the model is conveyed by the name of each type and instance in the model, which follows a specific naming convention and corresponds to the first column of the spreadsheet.

The scope of the VPL script is twofold: integrating the Revit data structure by creating new project parameters consistent with the typological spreadsheet, and inserting the values from the spreadsheet into Revit parameters (this operation can be repeated for data synchronisation).

The script shown in Part [0] of Fig. 5 introduces an interoperability component between the Excel spreadsheet and Grasshopper.

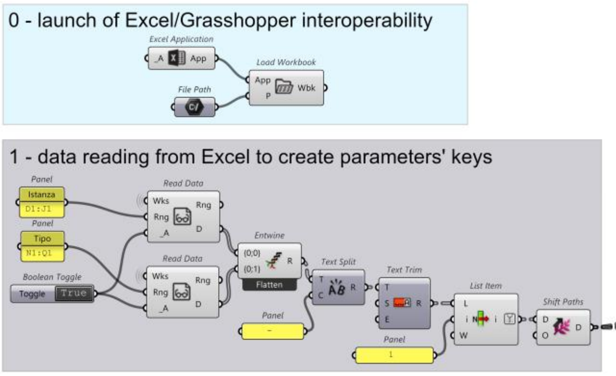

Fig. 5: VPL script - interoperability component and data reading from the Excel spreadsheet.

Part [1] of the script is dedicated to reading the first row of the spreadsheet that defines type (D1:J1) and instance (N1:Q1) parameters' keys, which are added in Revit (*Define Parameter*), mapped to the correct data level (*Add Parameter, Type or Instance*) [2] (Fig. 6).

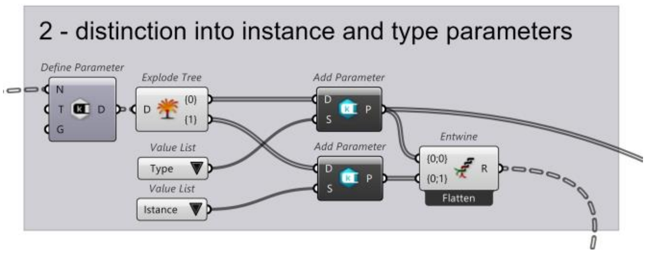

Fig. 6: VPL script - definition of instance and type parameters.

Part [3] implements the data structure of the model by filtering the elements belonging to the relevant construction categories (e.g. floor, wall, beam, structural framing, slab, etc.) and sorting them in the Grassopper data tree in the same order of the spreadsheet, to simplify the association of parameters (Fig. 7).

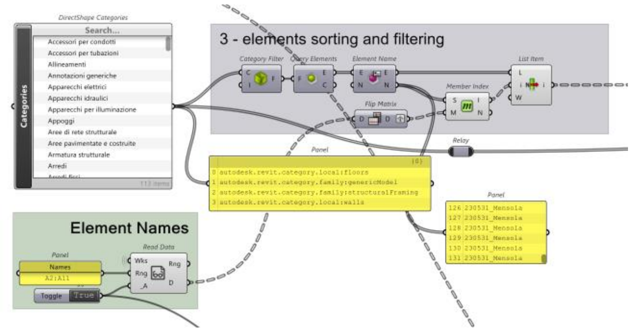

Fig. 7: VPL script – filtering and sorting of data in the grasshopper data tree.

The *Project Parameter* component inserts the type and instance parameters in the matching filtered and sorted categories [4] (Fig. 8).

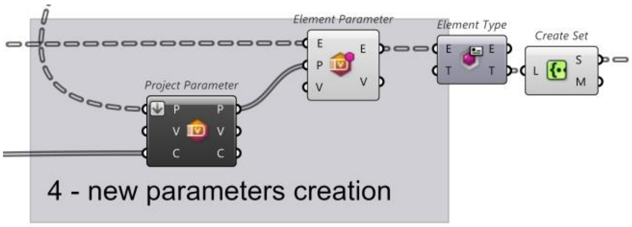

Fig. 8: VPL script - parameter definition from the filtered and sorted data.

Part [5] is devoted to writing the values of the new parameters, by reading them from the spreadsheet, mapping them to the corresponding parameters and sorting them to the single type/instances they belong to (Fig. 9).

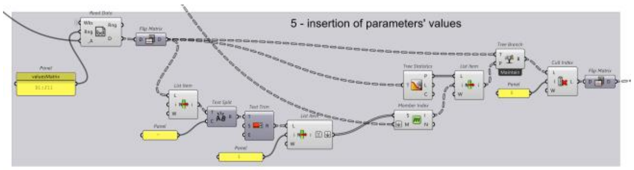

Fig. 9: VPL script – mapping and writing of the parameters' values.

Thus, the consistency and non-redundancy of the data structure and content are maintained, accommodating also updates in both the model and the spreadsheet, as long as data mapping is preserved. This allows different operators, for instance the BIM modeler, in charge of the model, and the conservation expert, in charge of curating the spreadsheet, to work independently, each with the most appropriate tool, within the same information management environment.

4. Conclusion

The current study tested an interoperability workflow, based on Visual Programming, to seamlessly integrate geometric and alphanumeric data from CAD modellers and spreadsheets into an HBIM model.

A VPL script recorded and controlled the geometric CAD-BIM interoperability process, to support the representation of complex elements, and the direct parametric modelling in the BIM environment, based on the geometrical tracing of architectural features on the point cloud. Similarly, the script managed the alphanumeric data implementation from spreadsheets, codified according to the BIM hierarchical structure.

The use of a specific VPL solution, fitting to natively bridge different software environments, allowed the seamless integration of different digital processes, selecting the most suitable for the task at hand, capitalising on each tool's potential and enhancing interdisciplinary collaboration between experts, who can work together, within a unified information management system, using their respective applications of choice.

The flexibility to define and adjust the VPL script reiteratively accommodates its adaptation to different contexts within a semi-automatic approach, by applying the same principles of geometric tracing, data mapping and interoperability to other building elements and contexts. This approach also confirmed the complementarity of different data modelling methods and demonstrated the effectiveness of Visual Programming to support the integrated digitisation of built heritage.

Limitations of the approach are linked to the ongoing development of the tools, which requires constant updating of the VPL scripts. Challenges also depend on the correct mapping of information within an interoperability process, because the data structure must be arranged according to each software environment's requirements, to avoid compatibility issues.

Future developments of the study include the testing of the workflow on different case studies, and its implementation to solve other interoperability issues, e.g. the modelling of more complex architectural shapes, the link with structural and/or energy simulation applications and the integration of other specific datasets of built heritage, for example on conservation state and decay patterns.

5. Acknowledgements

The study was developed within the INT4CT project (hIstory coNstrucTion for beauty CommunicaTion), coordinated by the Department of Architecture of Roma3 (DArc), coordinator Professor Antonio Pugliano, project code 305-2020-35602, funded by DTC Lazio Center of Excellence “Intervento TE1 - Invito al Centro di Eccellenza a presentare progetti per la seconda fase - Progetti RSI”. The DArc group involved in the INT4CT project developed the typological scheduling of the floor construction applied to the *Sala della piattaia* in Palazzo Altemps, and carried out the photogrammetric survey of the space.

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