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Materialisation of Complex Interior Spaces for the Insertion and Visualisation of Environmental Data in HBIM Models †

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Abstract: The Heritage Building Information Modelling (HBIM) methodology and environmental monitoring sensors are among the most widely utilised tools for the digital documentation of heritage buildings and the recording of changes in their environmental conditions. The creation of diverse methodologies for integrating sensor data and HBIM models is gradually becoming more prevalent, necessitating the development of alternative approaches to their integrated visualisation and analysis. This paper presents the findings of research conducted with the objective of establishing a 3D modelling process using Autodesk Revit® 2024.1 that allows for more accurate measurement of the interiors of heritage buildings with complex shapes. The interiors are then materialised and prepared to be tagged with informative parameters for 3D visual analysis within the BIM software itself. This process also makes it possible to export the data together with the 3D model to external platforms. To demonstrate the efficacy of this process, the church of the Real Colegio-Seminario de Corpus Christi in Valencia (Colegio del Patriarca), Spain, has been used as a case study.

Keywords: HBIM; 3d model; Revit; internal spaces; environmental sensors; Dynamo; preventive conservation; cultural heritage management

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1. Introduction

The field of architectural heritage plays an important role in contemporary society, serving as a reminder of the past, as a means of preserving the individual and collective identities of a people, and as a means of promoting tourism in the surroundings area [1,2]. The conservation of these buildings may entail a number of considerations, including the vulnerability of the structures to natural hazards, the pre-existing conservation conditions, the unique structural characteristics, the characteristics of the materials from which they are made, energy efficiency, and the effects of climate change. One of the factors that can contribute to the deterioration of heritage assets is public visitation. The continued growth of cultural tourism, coupled with inadequate planning for public use, represents an additional risk factor regarding the loss or degradation of heritage resources [3]. The excessive flow of people in an enclosed or confined space can alter the optimal environmental conditions for the conservation of the property. This can result in apparent deterioration of both the building and the collections it houses. This has been noted by the Preservation Institute of Canada since 1980 [4].

In light of the aforementioned circumstances, it is becoming increasingly crucial to implement measures aimed at preventive conservation. This entails the identification and control of variables and/or parameters of interest with the objective of minimising the deterioration of objects, goods or collections, as well as reducing the necessity for subsequent treatment of the aforementioned goods [5]. The term 'preventive conservation' is defined in the 2009 ICOM General Assembly as 'all those measures and actions that aim to prevent or minimise future deterioration or loss'. These measures and actions are indirect in that they do not affect the materials and structures of the property and therefore do not alter its appearance [6].

Preventive conservation measures entail the implementation of monitoring systems to evaluate the behaviour of these buildings, thereby generating valuable information that can assist in the design of maintenance and rehabilitation solutions [7]. In the case of heritage buildings that are open to the public, it is essential to monitor and record the indoor environmental factors (temperature, humidity and CO_2) [8] in order to protect the assets and ensure visitor comfort [9]. These data, together with visitor flow data, can have a significant impact on the conservation of a building and its internal collections [10]. The analysis of these data is essential for the management of preventive conservation, safety and visitor comfort.

The Heritage Building Information Modelling (HBIM) methodology is currently distinguished by its capacity to organise and archive semantic and geometric information pertaining to heritage buildings [11–17]. HBIM models have the capacity to store and manage data from a variety of monitoring systems, enabling the detection of potential threats to the conservation of buildings [18–21]. Research into the integration of sensors applied to heritage buildings and HBIM models is a growing area of investigation, with several lines of research emerging [2]. However, the integrated data lack alternative visualisation options within the software in which the building is modelled.

It is possible to identify publications that demonstrate the visualisation of sensor data within BIM models. Two such studies are those conducted by Kazado et al. [22] and Moreno et al. [23]. The aforementioned papers address different methodologies for integrating and visualising sensor data in BIM models, utilising Revit® software and tools such as DiRoots®, Dynamo®, Microsoft Azure, Power BI and Navisworks®. These methodologies are applied to buildings with relatively simple internal spatial forms, particularly in relation to their roofs, as is the case for the vast majority of new buildings. Furthermore, the visualisation of environmental data within Revit software is directly correlated with the delineation of rooms. In the study by Kazado et al. [22], the 2D visualisation is conducted using colour filters through the Dynamo programming platform, with the option of visualising them in 3D in the Naviswork software. In the study by Moreno et al. [23], the 2D visualisation is conducted with the use of colour filters through the DiRoots plug-in, with the potential for 3D visualisation through the Power BI data analysis tool. In the study by Moreno et al. [23], although it is feasible to visualise the colour filters in a 3D view of the Revit software, the colours are displayed on the room floors.

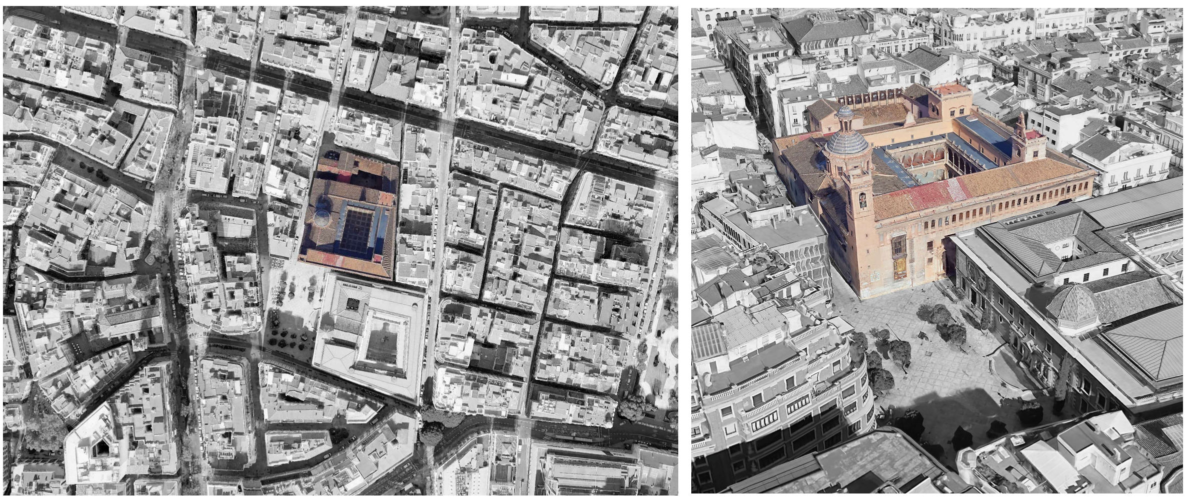
In the aforementioned cases, the method is highly effective for buildings with internal environments with simple geometric roof shapes, as it is relatively straightforward to obtain the volume data of the environments in the Revit software. However, when applied to heritage buildings, which tend to have internal environments with more complex roof shapes, such as ribbed vaulted enclosures, discrepancies emerge in the measurement of volumes. Consequently, in order to apply a comparable methodology to heritage buildings, it is essential to implement adaptations to the models in order to circumvent errors in volume calculations. Furthermore, the 3D visualisation of spatial volumes is conducted on external platforms that are distinct from the software utilised for the creation of the 3D model of the building. The capacity to visualise and analyse the data within Revit itself could potentially obviate the necessity for additional expenditures associated with the acquisition of alternative software or platforms and the training of professionals to utilise these tools.

The church of the Real Colegio-Seminario de Corpus Christi de Valencia (Colegio del Patriarca) was selected as a case study due to the fact that its interior, which is covered by ribbed vaults (Figure 1), serves as an ideal test laboratory for the process that has been developed. The selection of this building is also contingent upon the fact that this undertaking constitutes a component of the HBIM-SIG-Tourism research project conducted at the Universitat Politècnica de València. This project encompasses an investigation into the preventive conservation and management of public use of the aforementioned building, the Cathedral of Valencia, and the church of San Juan del Hospital. These three heritage buildings represent pivotal elements within the cultural and tourist offerings of the city of Valencia.

(**a**) (**b**)

Figure 1. (**a**) A view of the vaults of the choir and side chapels of the Colegio del Patriarca; (**b**) a view of the vaults of the nave and main altar of the Colegio del Patriarca. Source: Concepción López-González (2022).

The Colegio del Patriarca is a Renaissance architectural complex erected between 1586 and 1615, during the Counter-Reformation, for the education of priests according to the guidelines set forth by the Council of Trent [24–26]. The complex contains an important collection of paintings, which are exhibited in the museum, and one of the most significant archives of historical notarial records in Spain, comprising over 28,000 documents dating from the 14th to the 19th century. The building occupies an entire block in the Ciutat Vella district of Valencia, with the church being located in the south-west corner of the collegiate complex (Figure 2).



(**a**) (**b**)

Figure 2. (**a**) Location of the Real Colegio-Seminario de Corpus Christi in the historic centre of Valencia; (**b**) view of Colegio del Patriarca and the Plaza del Colegio del Patriarca. Source: own elaboration from images generated in Google Earth (2024).

This paper is an expanded version of the original communication, which was published in the proceedings of HEDIT 2024—International Congress for Heritage Digital Technologies and Tourism Management [27]. The objective is to enhance the modelling process, enabling more precise measurement of the complex internal spaces of heritage buildings and allowing for the materialisation of them in 3D volumes. This allows for the incorporation of informative parametric data obtained from sensors installed within the building. Furthermore, the potential for visualising the parameters within the modelling software and conducting a visual analysis of the spaces using a heat map is also explored.

The data inserted using the methodology employed in this study can be exported together with the 3D model and visualised in other platforms or software [28]. The process used in this study can be extrapolated to any other building with an internal environment enclosed by complex roofs, and thus can also be applied to the other two buildings studied in the aforementioned research project (Figure 3).

(**a**) (**b**)

Figure 3. (**a**) A view of the star-shaped ribbed vault of the Chapel of the Holy Chalice in Valencia Cathedral (source: Renan Rolim (2019)); (**b**) a view of the ribbed vaults of the presbytery of the church of San Juan del Hospital (source: Renan Rolim (2023)).

2. Materials and Methods

The developed process was divided into three phases, each employing a different set of tools (Table 1). In the initial phase, the Autodesk Revit 2024 software was utilised to generate a 3D model of the Real Colegio-Seminario de Corpus Christi in Valencia (Figure 4). This model was based on a point cloud provided by two researchers, PhD Junshan Liu, a Full Professor at Auburn University, and PhD Danielle S. Willkens, an Associate Professor at the Georgia Institute of Technology, collaborators in the HBIMSIG-Tourism project of the Universitat Politècnica de València. The second phase involved the materialisation of the interior spaces of the church as volumes in Revit itself, facilitated by the Autodesk Dynamo plug-in. In the third and final phase, the DiRoots plug-in was employed to filter the information inserted in the materialised volumes and to visualise it with a heat map.

Table 1. Phases and software used in the process.

Phase	Software
3D Modelling	Autodesk Revit® 2024.1
Materialisation of Complex Spaces	Autodesk Dynamo® v.2.18.1
Use of Heat Maps	DiRoots® One 1.6.0.0

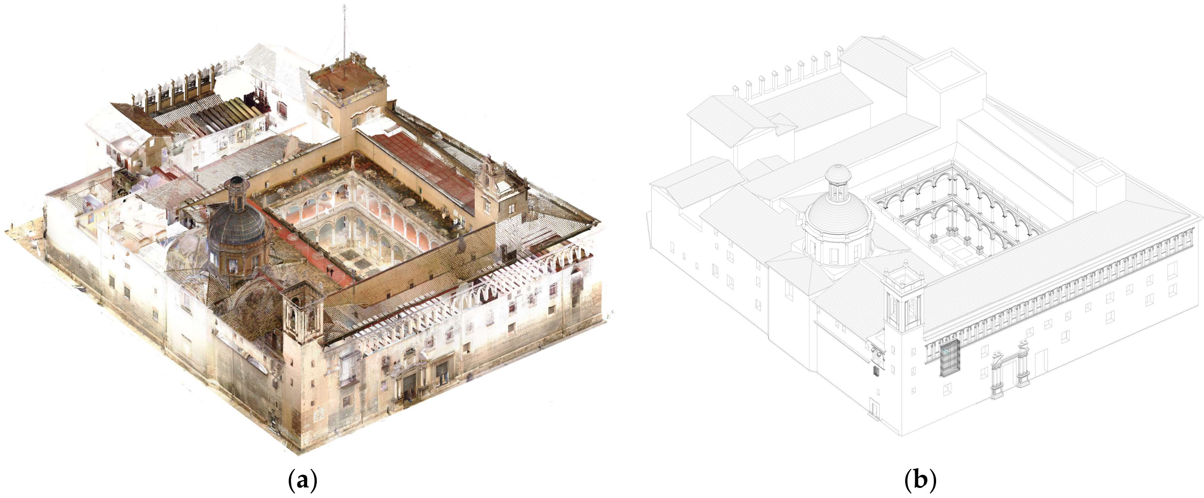


Figure 4. (**a**) Point cloud of Colegio del Patriarca (source: Junshan Liu and Danielle S. Willkens (2023)); (**b**) 3D model of the Colegio del Patriarca. Own elaboration from the point cloud taken in 2023 by Junshan Liu and Danielle S. Willkens.

2.1. Three-Dimensional Modelling

The 3D model was conceived as a comprehensive visual representation of the building, serving as a graphical and semantic database. It was designed to provide detailed information on the architectural elements, the materials used in its construction, and to include information sheets on the interventions carried out and its most important historical and artistic elements.

Subsequently, the installation of monitoring sensors in selected internal spaces was undertaken with the objective of preparing the database to receive information on the environmental conditions of these spaces. It was thus necessary to identify an alternative means of incorporating these data in a manner that would enable their visualisation within the 3D model, thereby facilitating real-time or short-term analysis of the environmental conditions prevailing within the building's spaces.

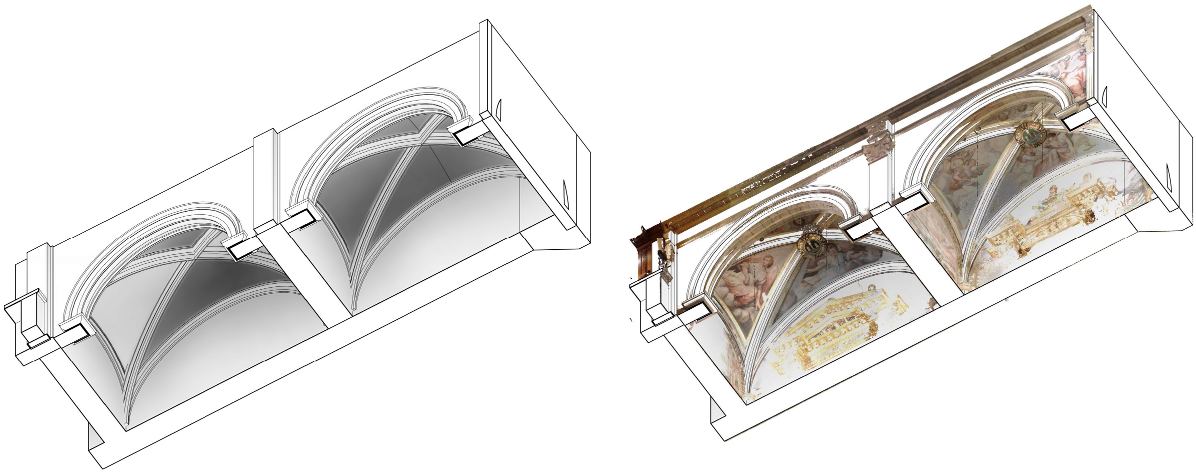
As the environmental data (CO_2, temperature, air pressure, relative humidity, condensation and saturation humidity) are entirely related to the volume of the space in which the sensors are installed, it was decided that these informative parameters should be inserted directly into the interior of the building.

It was resolved that the modelling process should commence with the most challenging component and proceed in a gradual manner, with the church of the Colegio del Patriarca being designated as the initial element for modelling due to the complexity of its internal spaces. During the modelling of the vaults of the side chapels, it was observed for the first time that the modelled vaults did not restrict the height of the native Revit tool 'habitation', resulting in an erroneous measurement of the volumes of the habitations.

The Revit software permits the semi-automatic acquisitions of area and volume measurements through the utilisation of the native 'room' tool. Typically, when utilising the 'room' tool, the option to measure volume is disabled and a default height for the environment is presented that is linked to the upper limit of the plane in which the room is situated. In this manner, the height of the room is not constrained by any element. In order for the room height to be taken into account in relation to any vertical limiting elements, such as a roof, ceiling, floor or curtain wall, it is necessary to activate this option in the 'Area and Volume Calculations' tool by clicking on 'Areas and Volumes'. Despite the activation of the aforementioned option, the results of the volume measurements of the modelled environments continued to exhibit inconsistences. To identify a solution to this issue, a series of 3D modelling tests was conducted on the church of the Colegio del Patriarca.

2.1.1. First Modelling Test

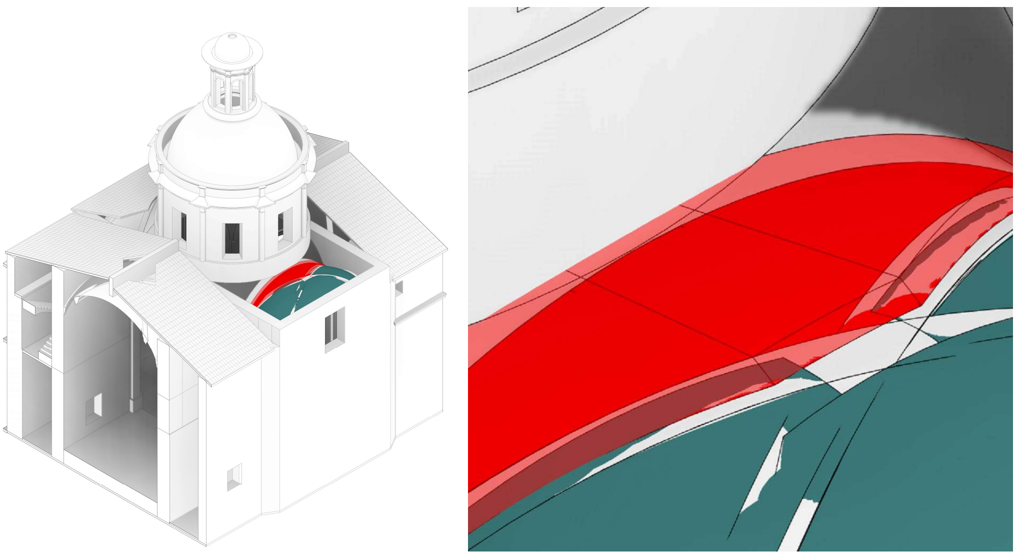
The initial test was conducted on the modelling of the rib vault plementeries, where the 'mass' tool was initially employed. The plementeries were modelled individually in accordance with the precise representation of the point cloud. The initial result was found to be in close alignment with the original representation of the building (Figure 5).



(**a**) (**b**)

Figure 5. (**a**) Bottom view of the modelling of the vaults using the mass tool; (**b**) bottom view of the modelling of the vaults using the mass tool with the point cloud overlay. Source: own elaboration (2024).

An attempt was made to augment the thickness of the mass layers generated by the tool in order to create solid shapes that would more accurately represent the vault plementeries. However, the resulting outcome was found to be unsatisfactory, as the extrusion of the mass layers introduced triangulation errors that deformed the surfaces of the plementeries (Figure 6).



(**a**) (**b**)

Figure 6. Error in the extrusion of the mass layer. (**a**) In green: plementeries modelled with the mass tool; in red: error presented in the plementeries when the extrusion was performed on the created mass; (**b**) detail focused on the error presented in the plementeries. Source: own elaboration (2024).

In addition to the triangulation errors, the massing layers did not impose any constraints on the height of the rooms (Figure 7). At the time of this initial test, it was only possible to visualise the room height constraint errors through the 2D sections of the model.

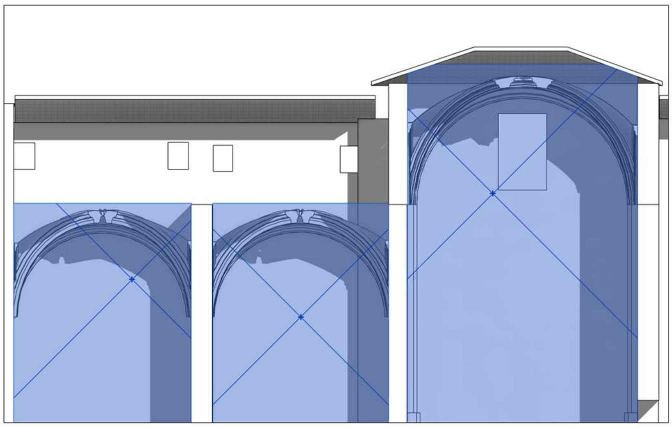


Figure 7. Visualisation of the vaults using the 2D section in Revit 2024, demonstrating that the height of the spaces is not constrained by the mass surfaces generated. Source: own elaboration (2024).

In light of the unsatisfactory outcome of the initial test, further tests were conducted with the objective of identifying novel modelling alternatives that would serve to constrain the height of the rooms.

2.1.2. Second Modelling Test

In the second test, an attempt was made to convert the mass layers created in some of the families that limit the heights of the rooms, specifically the curtain wall, roof, ceiling and floor. The mass layers representing the transept vaults, which exhibit more open angles, permitted the conservation of the mass to the curtain wall or roof. Nevertheless, the mass layers representing the transept vaults and the side chapels, with narrower angles, did not permit this conversion due to the complexity of their geometry.

The massing layers that permitted conversion to curtain walling necessitated modifications to their mullions and the concealment of select elements. Moreover, all the layers that allowed conversion in some of the families that limit the height of the rooms exhibited inconsistences without limiting the heights between the connections of the plementeries or between the connections of the plementeries and the walls of the rooms (Figure 8).

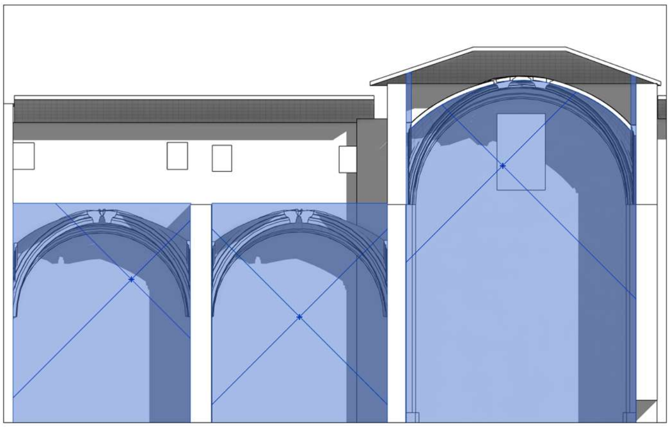


Figure 8. Visualisation of the vaults using the 2D section in Revit 2024, demonstrating that the mass surfaces that allowed for the conversion to the roof now limit the height of the spaces. Centre and left: mass surfaces that did not allow conversion; right: mass surfaces that allowed conversion but still required manual adjustments. Source: own elaboration (2024).

Given that the errors identified thus far were only visible in the 2D sections, a method was sought to visualise them in 3D, thereby facilitating more accurate localisation within the plementeries. The optimal solution for achieving this objective was to utilise Autodesk Dynamo visual programming software.

Dynamo enables the creation of routines for the customisation of workflows, automation of tasks and generation of complex geometries. Furthermore, it is also fully integrated into the Revit software through a plug-in, functioning as an extension of Revit itself. This integration enabled building modelling, which was a pivotal factor in its selection. As a result of this integration, a routine has been established that enables the 3D visualisation of errors in the plementeries, facilitating their identification within the 3D model (Figure 9).

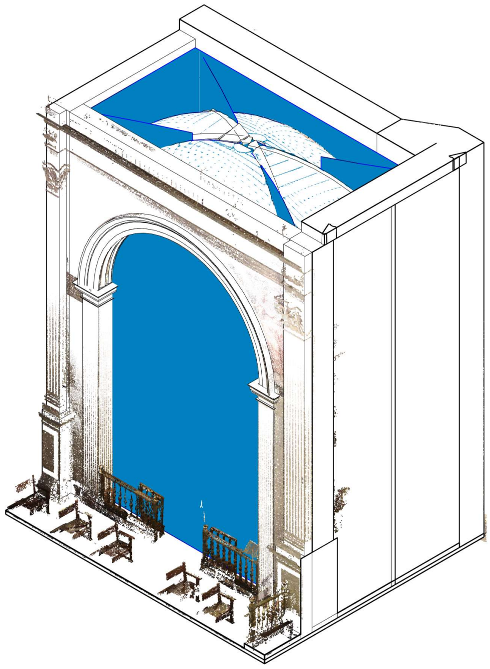
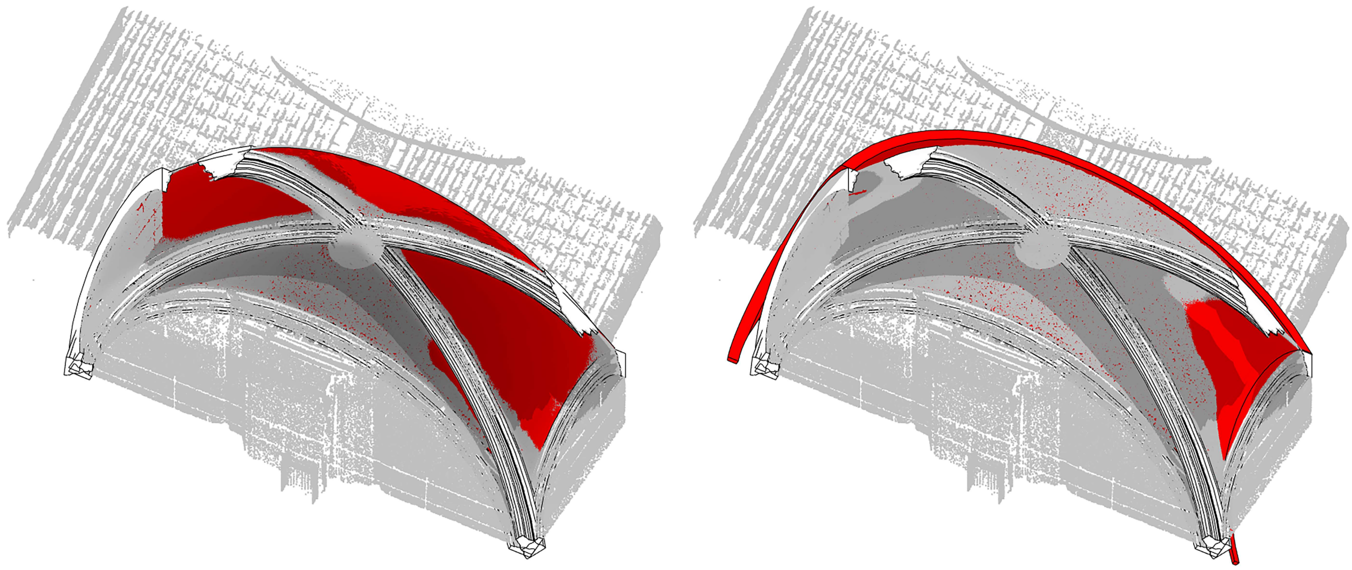


Figure 9. Materialisation of the interior spaces of a side chapel using the Autodesk Dynamo plug-in. In blue: materialised volume with errors in the connections between the plementeries and between the plementeries and the walls. Source: own elaboration (2024).

The 3D visualisation revealed that the connections between the plementeries and between the plementeries and the walls required significant modifications. In view of the unsatisfactory outcome of the second test, further tests were conducted to achieve a positive result.

2.1.3. Third Modelling Test

In the third test, the utilisation of mass layers was abandoned and the plementeries were modelled using the roof family. In contrast to the initial and second tests, where the plementeries were modelled in isolation, an endeavour was made to model them as a singular element. The outcome permitted the height of the rooms to be constrained, yet the resulting geometry exhibited a notable divergence from the point cloud and vault modelling, displaying greater visible discrepancies than when modelled with the mass layers (Figure 10).



(a) (b)

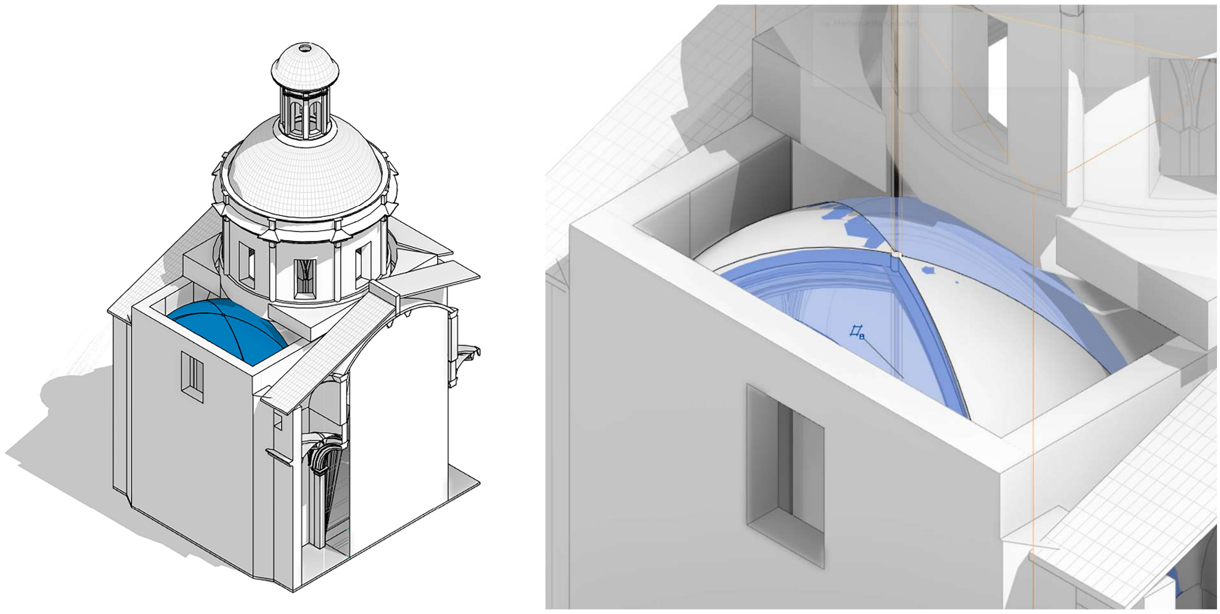
Figure 10. Overlay of the point cloud (in grey) and the 3D model (in red) of the vault showing the geometric divergence between the modelled vault and the point cloud. It can be seen that the vault modelled separately as a mass layer (**a**) is visibly more accurate than the vault modelled as a single element (**b**). Source: own elaboration (2024).

In light of the inaccuracies observed in the modelling of the vaults as a singular element, the plementeries were once more subjected to an isolated modelling process, this time within a group and utilising the roof family. The process involved the use of volume creation tools, including extrusion, sweep, rotation and subtraction elements. However, this method of modelling still demonstrated the same errors in the connections of the studs and the connections of the studs to the walls, as had been observed in previous tests.

In order to eliminate the errors in the connections between the studs, a new procedure was attempted which involved modelling the plementeries facing each other as if they were a single element within the group (Figure 11).

This method proved effective in addressing the majority of the issues pertaining to the connection between the plementeries. However, residual errors persisted in the keystone and in the joints between the plementeries and the walls, which were not orthogonal. The errors between the plementeries and the walls were rectified by extending them to the central axes of the walls. Similarly, the errors in the keystone of the vault were addressed by incorporating a minor circumference at the juncture of the plementeries to prevent them from coming into contact.

These modifications permitted the constraint of the room height, which proved to be an adequate outcome. Ultimately, an effort was made to further streamline the modelling process, as it was observed that, if the plementeries are initially delineated as isolated elements that are situated outside of a group and which utilise the roof family, there is no necessity to set the central circumference in order to prevent contact between them, thus maintaining the obtained favourable result.



(**a**) (**b**)

Figure 11. In blue: modelling of the plementeries separately and within a group (**a**); detail of the modelling of the plementeries facing each other and the small circumference made at the junction of the plementeries (**b**). Source: own elaboration (2024).

3. Results

3.1. Materialisation of Complex Spaces

In order to ascertain the shapes that presented errors when generating volumes in Revit using the Dynamo plug-in, a series of tests was conducted. The results demonstrated that simple shapes, including cubes, parallelepipeds, prisms and hemispheres, could be generated and displayed perfectly on both the Autodesk Dynamo plug-in screen and the Autodesk Revit software screen (Figure 12).

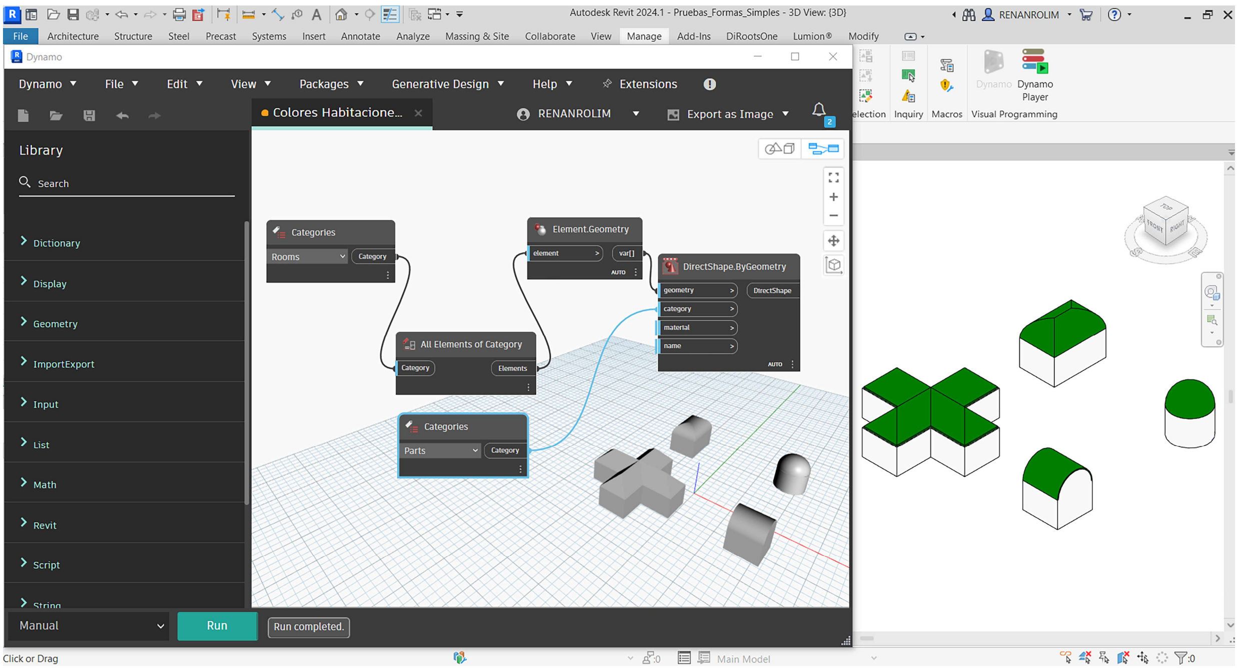


Figure 12. Materialisation in Revit of the interiors of simple shapes using the Dynamo plug-in. In this case, it is possible to visualise them in both Revit and Dynamo. Source: own elaboration (2024).

In the case of more complex geometric shapes, such as ribbed vaults, the integration between Revit and Dynamo has some limitations. For example, if complex vaults correctly constrain the height of the environments, the generated volumes can be visualised on the Revit screen. Conversely, if complex vaults have errors in constraining the heights or do not completely constrain them, it is possible to visualise the errors on both the Revit and Dynamo screens (Figure 13).

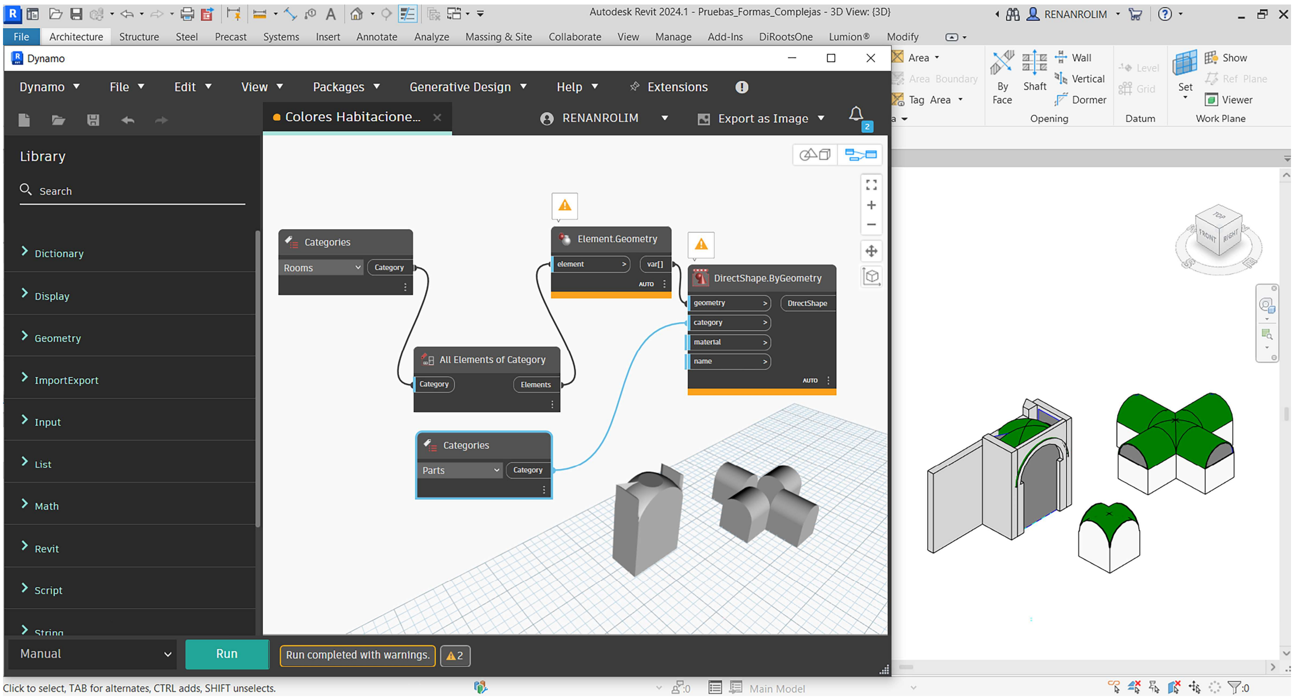


Figure 13. Materialisation in Revit of the interior spaces of complex shapes using the Dynamo plug-in. In this case, it is only possible to visualise some types of errors in Dynamo. Source: own elaboration (2024).

It is feasible to materialise and ascribe informative parameters to the generated volumes through the utilisation of the 'mass' and 'part' categories. Although not the primary focus of this research, supplementary tests were conducted to export the 3D model with volumes and associate parameters to a Geographic Information System (GIS) platform [28]. The utilisation of the 'part' category facilitated more effective identification and manipulation of the volume data within the GIS platform, resulting in enhanced outcomes. Accordingly, the 'piece' category was selected as the standard for materialising the volumes of complex spaces.

In regard to the materialised spaces, it was possible to prepare them to directly receive the informative parameters related to the data collected by the environmental sensors installed in the case study, namely CO_2, temperature, atmospheric pressure, relative humidity, condensation and saturation humidity.

3.2. Use of Heat Maps

In order to filter the informative parameters inserted in the materialised spaces, the DiRoots plug-in was employed. This is a free plug-in that is straightforward to install and utilise, and it has been designed to integrate seamlessly with Autodesk Revit. This approach enables the filtration of information from the created parameters, and the assignment colour ranges from the lowest to the highest index, allowing the materialised spaces to be visualised as a 'piece' in a heat map within the software itself. The heat map can be visualised in both the plan and in the 2D and 3D sections within Revit, thus facilitating a simplified visual analysis of the internal environments of the case study (Figures 14–16).

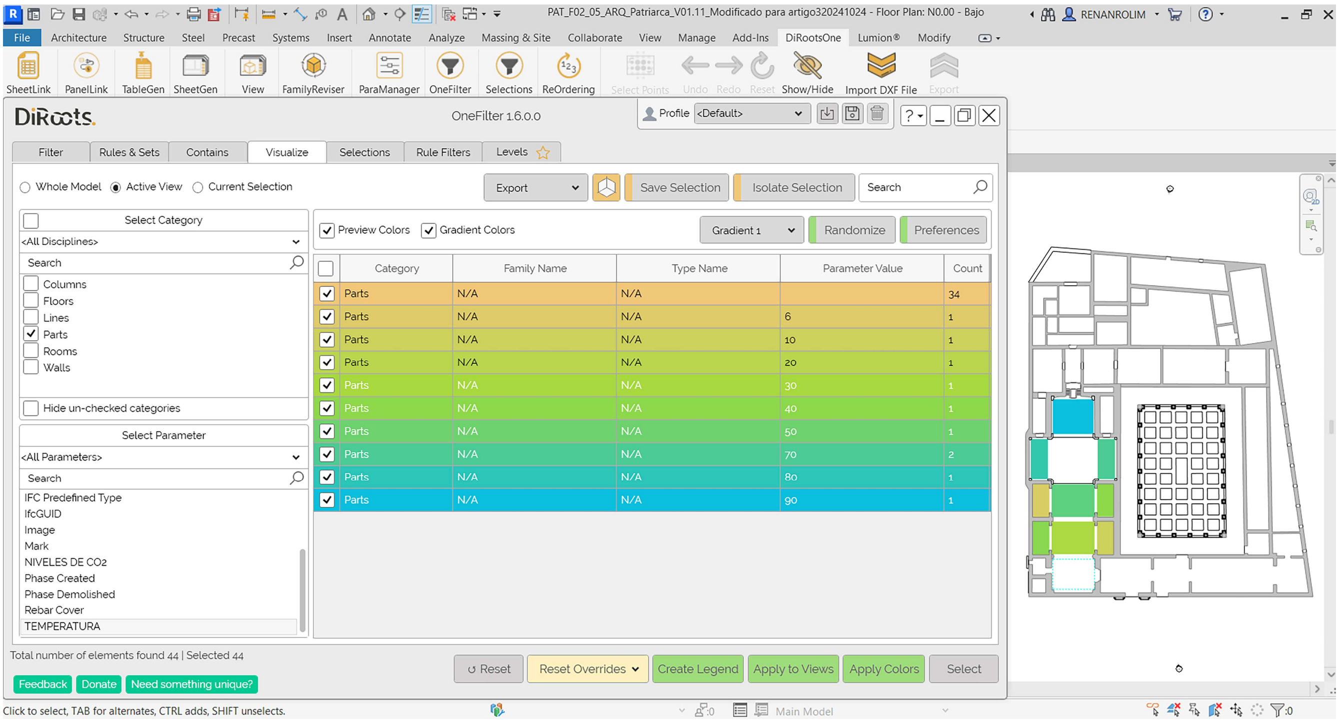


Figure 14. Visualisation of the heat map in Autodesk Revit 2024 using the DiRoots plug-in filter. On the left, filters applied in DiRoots to detect the parameters inserted into the internal spaces materialised as 'pieces'. On the right, visualisation in Revit of the heat map on the ground floor. Own elaboration (2024).

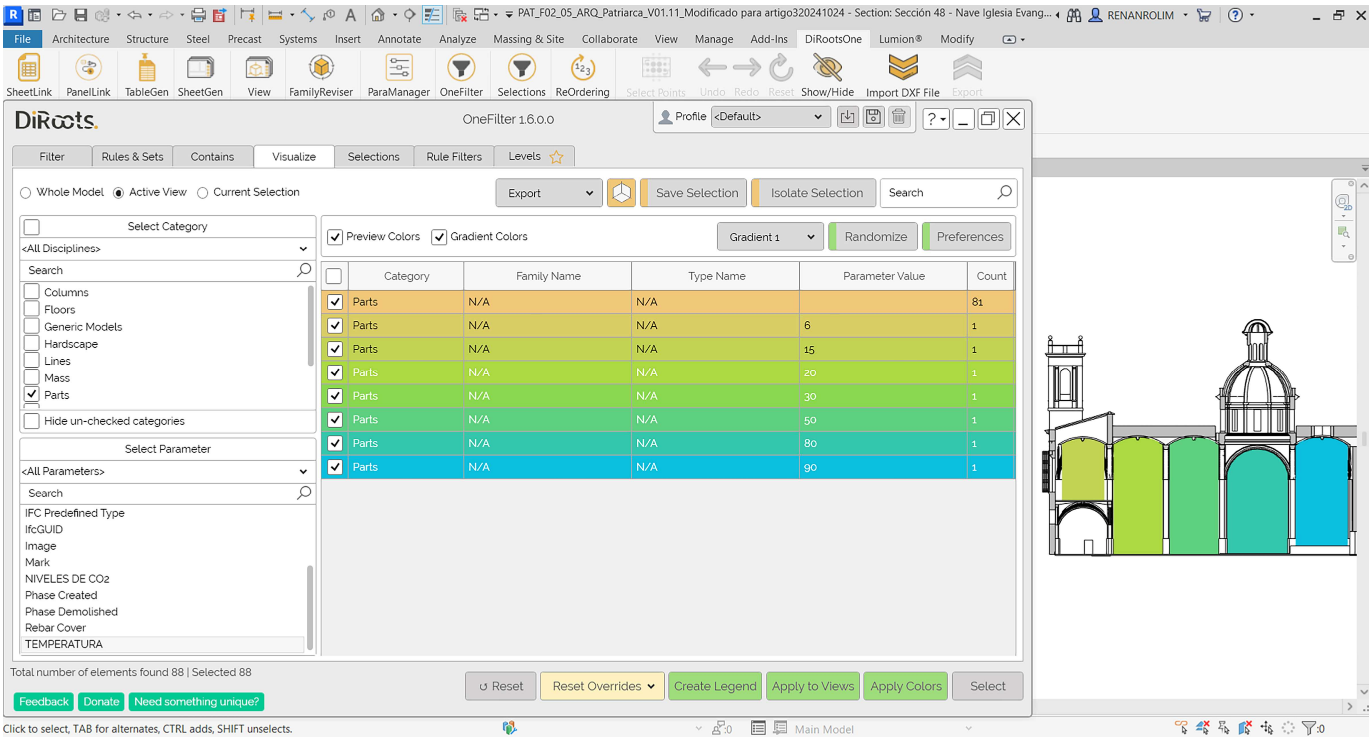


Figure 15. Visualisation of the heat map in Autodesk Revit 2024 using the DiRoots plug-in filter. On the left, filters applied in DiRoots to detect the parameters inserted into the internal spaces materialised as 'pieces'. On the right, visualisation in Revit of the heat map in the 2D section. Own elaboration (2024).

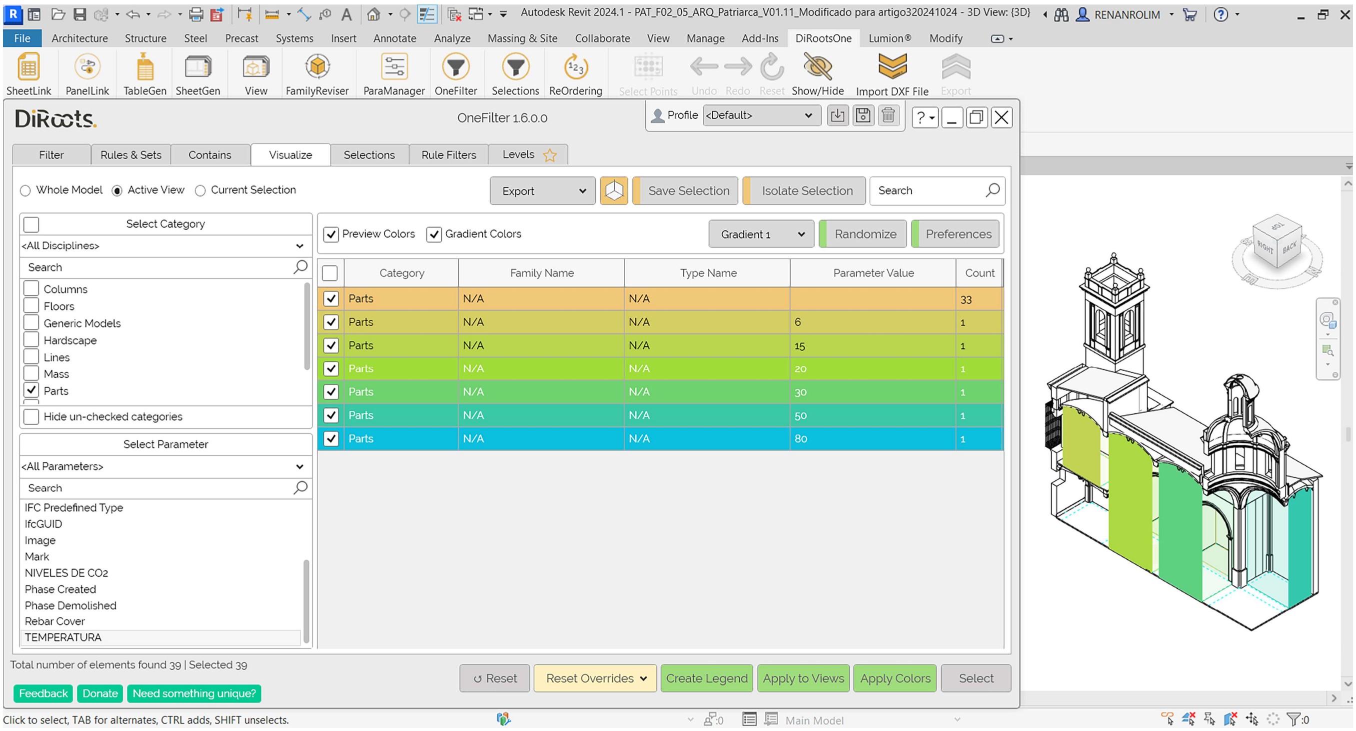


Figure 16. Visualisation of the heat map in Autodesk Revit 2024 using the DiRoots plug-in filter. On the left, filters applied in DiRoots to detect the parameters inserted into the internal spaces materialised as 'pieces'. On the right, visualisation in Revit of the heat maps in the three-dimensional section. Own elaboration (2024).

4. Discussion

The Autodesk Revit 2024 software is capable of automatically calculating the areas of a building's interior spaces through the utilisation of the 'room' tool. However, in order to calculate the interior volumes of the aforementioned spaces, manual adjustments are required to limit the height. Furthermore, the volumes generated by the room tool were only visible through the 2D section of the model and did not permit the assignment of informative parameters.

The native Revit 2024 tools, including roof, ceiling, floor and curtain wall, were observed to perform effectively in limiting the height of relatively simple geometric shapes, such as pitched roofs, gable roofs, hipped roofs, domes, barrel vaults and groin vaults. However, when applied to more complex shapes and surfaces, such as ribbed vaults, the software exhibited inconsistencies in the limits and, consequently, in the measurement.

The methodology developed in this study enables precision in calculating the volume of interior spaces of complex shapes, which can assist in the more accurate calibration of climate control systems in heritage buildings. This, in turn, allows for the calculation of the requisite air exchange, thus preventing extreme variations in temperature, humidity and CO_2. These variations can lead to degradation processes, such as the formation of condensation and carbon dioxide, which can damage architectural and structural elements as well as the building's works of art. Furthermore, more accurate measurements of volumes could assist in the calculating of the carrying capacity of visitors in accordance with the environmental conditions of heritage buildings, thereby avoiding situations that could affect their comfort and put their safety at risk.

The materialisation of these spaces in 3D and the assignment of informative parameters related to the environmental data collected by the sensors has enabled the integration of information on the environmental conditions of the internal spaces directly into the building database. This integration allows for the visualisation of these conditions in the colour ranges by means of a heat map. In contrast to the 2D visualisation, the 3D heat map provides an overview of the building levels and facilitates the identification of potential issues. Additionally, modifications can be made to the visualisation using sections in the Revit 3D view, thereby enabling a visual analysis of the environmental data and extending the visualisation capabilities of the data that are directly integrated into the software through which the visualisation is modelled.

Furthermore, the volumes created and the parametric information inserted can also be exported together with the model to other visualisation and analysis platforms, such as a GIS [28], since it is possible to extrapolate them to other buildings with different morphologies and uses. In this manner, the integrated data can be visualised and analysed within the software in which they were modelled, as well as in other platforms or software, individually or together with other buildings. This allows for a comparative analysis of the buildings, which can assist in defining priorities for preventive conservation actions and in managing visitor flows, thereby facilitating decision-making by managers.

5. Conclusions

The employed methodology has rectified the inaccuracies in the ‘room’ tool of the Revit software, which saw the heights of rooms with complex ceilings being erroneously calculated with limited measurements. This enabled more precise measurement of the internal volumes of these types of spaces.

The integration of the Revit software with the Autodesk Dynamo and DiRoots add-ons has facilitated the development of a process of 3D materialisation of complex spaces and their visualisation in a heat map within the software in which they are modelled. This has enabled the integration of external information and the performance of analyses without the need to export the data to other platforms or visualisation software. Furthermore, the methodology allows for the exporting of the integrated data, along with the 3D model, to other external platforms, such as a GIS.

The standard level of geometric information and the level of detail that the 3D model should have in order to monitor the environmental conditions of the interiors of heritage buildings have yet to be defined within this methodology. The model used in this case study had some limitations due the fact that its purpose was changed at the time of its creation. This resulted in some errors in the materialisation of some spaces when some elements were considered as part of the limiting element of the height of the spaces, such as when the ribs of the vaults were included as part of the roof. In addition, adjustments must be made to the connections of the interior spaces, which can also lead to errors in the measurement of the spaces.

The process could also be improved by adding nuances in the colour ranges applied to the volumes, which would provide an even more detailed colour map, and by using artificial intelligence to automate some actions in the process, such as materialising spaces or integrating sensor data with Revit software in real-time or in the short term.

The results of this study may assist researchers seeking to integrate data from different types of sensors and HBIM models, as well as those seeking alternatives in regard to heritage conservation and visitor management. This methodology is also well suited for risk management in heritage buildings.

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