

USE OF BIM MODEL IN THE DESIGN OF THE RENOVATION OF HISTORIC BUILDINGS

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Abstract

The article explores the practical application of Building Information Modelling (BIM) in renovating historical buildings, focusing on the digitalization process and the integration of fourth and fifth dimensions into the information model. It addresses challenges encountered when working with irregularly shaped buildings lacking preserved project documentation. Additionally, it examines the advantages and disadvantages of linking 3D elements with time and cost considerations. The authors present a methodology, a sequential approach tailored for BIM model utilization in historic building restoration, which was specifically validated through a case study of a historic church building in Rudník village. The methodology proposes a comprehensive framework applicable to the restoration of various historical buildings. The article contributes a generally applicable methodology for leveraging BIM models in historic building restoration, facilitating design and implementation processes across diverse historical contexts.

Keywords

BIM model, historic building, renovation, 3D model, scheduling

1 INTRODUCTION

Historical buildings and cultural monuments represent a piece of history that needs to be preserved, not only out of respect for the created structures, but also for the preservation of key indicators of human activity spanning decades, centuries, or even millennia.

Unfortunately, not all historical buildings have preserved project documentation, which hinders the smooth and precise planning of their restoration. From a more precise perspective, only a few structures are classified as cultural heritage with intact and complete project documentation, and when it comes to possessing a 3D model, this percentage approaches nearly zero [1].

This fact presents a certain complication in the process of restoring historic buildings. Without project documentation and, in today's context, without a 3D model, restoration planning is often imprecise, and in most cases, the quantity survey only provides approximate figures. This leads to inexactly calculated costs for the entire restoration process and the incorrect creation of a timeline [2], [3].

This article will explore whether it is possible to use Building Information Modelling (BIM) when designing the restoration of historical buildings and how the use of information modelling can simplify or, conversely, complicate the restoration process. In addition to modelling and digitizing the structure itself, the article will also focus on the actual restoration design. The research will investigate whether it is possible to elevate the 3D model of a historical building to the level of a BIM model by adding the fourth and fifth dimensions, i.e., tracking time and costs and directly linking them to the 3D elements of the structure. This step could prove beneficial not only from the public's perspective in better understanding the restoration process but also from the investor's viewpoint for precise cost control. It will also benefit the contractor, who will have a clear visualization of where and how individual processes will take place, providing an overview of the restoration even before its implementation [4].

A review of the scientific literature in the Scopus and Web of Science databases shows that of the total number of papers related to BIM and renovation, only 13% are devoted to heritage BIM (H-BIM). This scarcity points to an early stage of research in this field. In particular, the article entitled 'Implementation of HBIM on heritage restoration projects' highlights the under-researched link between heritage restoration practices and BIM technologies, emphasising the need for a coherent approach to support post-restoration management plans.

This paper attempts to bridge this gap by exploring the feasibility and implications of using BIM in the restoration of historic buildings. Central to this exploration is the question of whether BIM can make the restoration process more efficient or, conversely, more difficult. In addition to the digitisation itself, the study aims to assess the potential of extending 3D models to include a fourth and fifth dimension, integrating time and cost parameters, thereby offering stakeholders a comprehensive tool for planning, cost estimation and project management [4].

By elucidating the challenges and opportunities inherent in the intersection of BIM and the restoration of historic buildings, this research aims to contribute to the growing body of knowledge in the field of BIM in the cultural heritage sector and offer insights that are key to informed decision making and sustainable preservation efforts [1].

2 METHODOLOGY

The objective of this paper is to propose a methodology for utilizing Building Information Modelling in the restoration of historical buildings and to subsequently validate it through the case study – the restoration design of the Church of St. George in the village of Rudník.

Research material

To demonstrate the use of the BIM model, a case study of St. George's Church in the village of Rudník was developed. In the specific case, the objective of the renovation was chosen, namely the restoration of the roof covering and the restoration of the facade.

The historical building of the Church is located in the village of Rudník, which is part of the Slovak Ore Mountains (Slovenské rudohorie). The village is situated in the eastern region of Slovakia, specifically in the Košice Region, west of Košice itself. Today, the village covers an area of 2300 hectares and has a population of 614 residents [5].

The dominant structure in Rudník is the Church of St. George, which was constructed in 1692. In 1842, the church building was demolished, and a new one was erected in its place, serving as a Roman Catholic school [6].

The church is built in the Neoclassical style and consists of a single nave space terminated by a semicircular apse and an integrated tower. A sacristy was later added to the building. The open interior of the church is adorned with vaults along its sides. The church's facade is adorned with semicircular windows and pilasters. The roof is varied, primarily gabled with a semicircular spire, while a shed roof is situated above the sacristy, and a bell-shaped roof is found above the tower. The church's tower is situated at the front of the building, protruding the full height of the structure, housing the entrance portal [6], [7].

For the implementation of the facade restoration, an architectural proposal titled "Facade Restoration Project" was created in October 2020. The proposal was prepared by Ing. Peter Tegza, who, based on a visual inspection of the actual condition, identified the causes of the facade's damage. It is evident from the proposal that the church's facade is primarily damaged by rainwater flowing freely from the church's roof, causing corrosion of the plaster. In the picture below (Fig. 1) you can see the actual state of the church's facade from the year 2020. The plaster in these areas has damaged almost the entire surface, with the most affected areas being around the windows and pilasters.



Fig. 1 The actual state of the church's facade (Facade Restoration Project).

The material composition of the facade is based on this facade restoration proposal and also on the input from the Regional Monuments Office in Košice. Although the building is not classified as a national cultural monument, it is advisable to proceed with the restoration as if it were, in order to prevent possible deterioration of the structure.

The architectural proposal for the façade restoration also addresses the prevention of water damage to the plaster caused by rainwater. To prevent rainwater from flowing down the plaster, the project suggests replacing the roofing structures of the church. The new drainage system needs to either connect to the sewage system or involve the creation of a drainage trench around the church, which will divert water away from the church's surface into green areas.

As part of the roof covering restoration, there will be a renewal of layers of the roofing material to the roof truss. In the case of replacing the roof covering, it is essential to ensure that the new material adheres to traditional materials and traditional forms. This could include options such as folded sheet metal roofing, metal templates, or small-format ceramic tiles. The proper roof design also requires input from a structural engineer to verify the load-bearing capacity of the roof truss.

Research methodology

The concept of Building Information Modelling (BIM) revolves around tracking a construction project from its initial idea all the way to its demolition. It connects physical elements with logical ones, making it possible to create a digital version of a building that includes all information related to the structure [8], [9].

BIM doesn't just represent the concept of a three-dimensional model; it also integrates additional information and breaks down the entire life cycle of a construction project into dimensions. An information model consists of 10 dimensions (Fig. 2), which collaborate and interact with each other. These dimensions are further categorized into two groups. The first group comprises the standard dimensions, which include dimensions 1–7, covering everything from the initial idea to facility management. The second group consists of new dimensions, namely 8–10, encompassing safety during design and construction, as well as the industrialization of the construction process [8], [9].

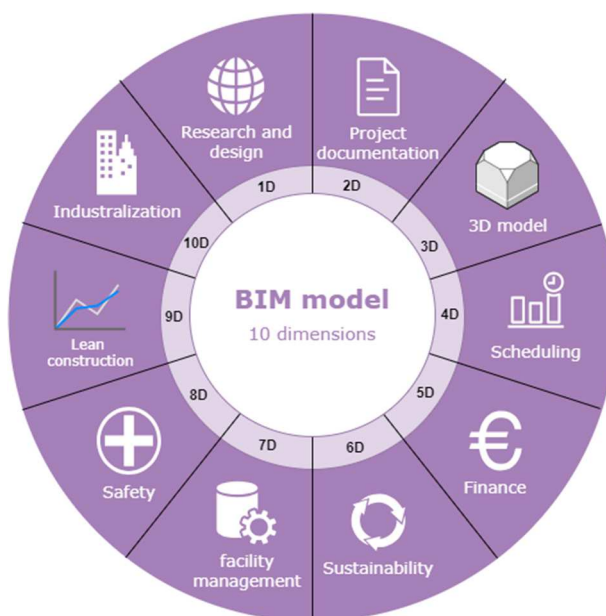


Fig. 2 The BIM model divided to 10 dimensions [8], [9], [11].

The entire structure of a BIM model is not rigidly defined, and each construction project must be approached individually. The scope of dimensions depends on the purpose and extent of the construction. The BIM model concept is built on two main principles: communication and collaboration. Team members continually add and refine the project, recording and modifying the changes in all related dimensions to make working with the project more efficient and the resulting model as accurate as possible [10].

The **first dimension** of the BIM model shows the tasks associated with the research and design of the project design. In this part, the real environmental conditions where the building is intended to be constructed are ascertained. Information is gathered about the existing buildings located on the site. The climatic conditions of the environment or, for example, the orientation of the sun and the shadows it produces on the site are also examined [11].

The **second dimension** is also known as the design phase of building design. It includes the creation of all the necessary design documentation documents. This dimension represents the architectural and technical design of the building shown only through 2D documents. In addition to drawings of floor plans, sections and views, 2D also deals with the creation of interactive tables linked directly to the project [11].

Numerous people think of the term BIM as a 3D model of a building. However, the **third dimension** cannot be considered synonymous with the word BIM model. It is just a three-dimensional representation of the proposed construction. This part creates a digital version of the building from the 2D documentation. In addition to the 2D documentation, a 3D model can also be created in the third dimension from a point cloud, which is the output from laser scanning or photogrammetry. The creation of a digital model does not only serve for the visual representation of the proposed building, but also allows the creation of various visualizations, rendering of views and also the creation of video recordings of the called virtual walkthroughs of the digital model [8], [11].

The **fourth dimension** adds a time parameter to the project. Time planning is used to organize construction production. It is a process through which contractors are able to predict the duration of the entire construction, determine the dates of important milestones, but also efficiently allocate the resources needed to carry out the work activities. Traditional scheduling methods are static in nature, which means that they often do not offer the ability to dynamically add information or manage construction production openly. It is the fourth dimension of the BIM model that offers the ability to visualise the progress of construction, to actively change and update time information, and also the ability to manage site safety during construction. The fourth dimension is a tool that makes it possible to create intelligent connections between scheduling information and the 3D model. 4D allows to achieve better control over the entire project, to plan more efficiently, as thanks to the links it provides and the visualization of the growth of the construction over time, it is possible to better anticipate events and thus reduce the time and the associated costs of the entire process of construction and implementation of the construction work [12], [13], [14].

The **fifth dimension** represents more efficient construction cost estimation. With 5D, it is possible to make intelligent connections with 3D model information and project cost information. When incorporating the fifth dimension into a BIM model, it is necessary to divide the 2D and 3D parts of the project and define the parametric elements of the construction. Parametric objects in the project can be walls, columns, windows, doors, etc. Parameterizing elements are the combination of geometric information with other descriptive properties and their relationships to other elements in the model. It is a method whereby modifying one element automatically corrects all adjacent elements or assemblies so that the previously defined relationship between them is preserved. The fifth dimension is represented by the set of operations leading to the creation of the estimation and analysis of the costs necessary for the implementation of the project with reference to the BIM model. The biggest difference between traditional costing and 5D modelling is the speed of updating the budget. By integrating with the third and fourth dimensions, changes to the project can be captured more efficiently and thus the cost amount can be changed [8], [13].

The sustainability of the project is addressed by the **sixth dimension** of the BIM model. Sustainability is the effort to build objects that, by their existence, do not negatively affect the environmental, economic, or social aspects of the Earth and the lives of other organisms and people around them. The sixth dimension of the BIM model allows the energy intensity of a project to be investigated at the preliminary stage. It addresses all aspects related to the sustainability of the construction such as waste disposal details, energy requirements, maintenance schedule, etc. [8].

The **seventh dimension** is used to create and analyse the construction maintenance plan. This part of the BIM model deals with Facility Management, a set of activities used to manage all aspects of an existing building. The content of this dimension is the optimal management of the building structure throughout its lifetime. Information related to material warranties and building maintenance documents is accurately assigned to the building elements in the structure, thus achieving the linking of the 7D with the 3D geometric model of the building and the entire BIM model. The seventh dimension is modelled before and during the construction of the building object, but the greatest use of the seventh dimension comes on the longest stage, during the use of the building object [8].

These seven fundamental BIM dimensions are complemented by three new dimensions. The **eighth dimension** represents safety on site in BIM models. This part of BIM modelling examines and analyses the potential risks and hazards that may occur during the project. The main advantage of 8D is the creation of a complete site simulation with all possible hazard scenarios. It allows to identify and design, precise protective equipment solutions for a specific project [9], [12].

Lean construction in BIM model is represented by the **ninth dimension**. It is the process of streamlining and optimizing all steps related to project execution and digitizing construction. Through lean construction, it is possible to control and minimize construction waste and optimize the use of materials. By tracking the use of construction materials, it is possible to efficiently convert potential waste into resources [8].

The last **tenth dimension** is used to industrialize the building. The concept of construction industrialization means bringing new technologies into the implementation process that help to increase the productivity of

construction. Achieving the tenth dimension is possible by adding various design and digitization tools for construction [8].

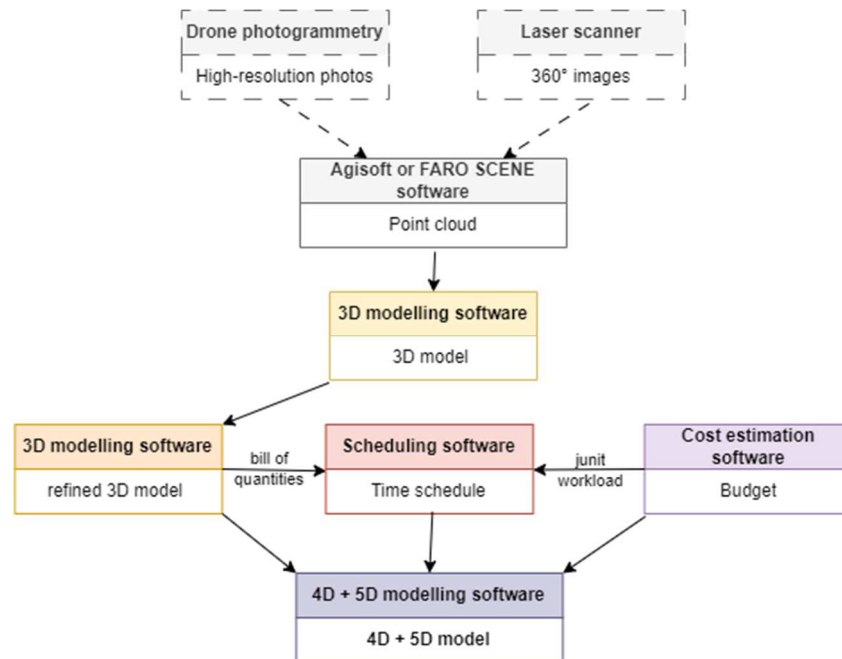


Fig. 3 Hierarchy of inputs and outputs in 4D and 5D model creation (work of author).

The diagram (Fig. 3) shows the hierarchy of inputs and outputs required in creating the fourth and fifth dimensions. From the initial inputs in the form of photographs and 360° images created by the laser scanner, through the import of the point cloud and the creation of the 3D model, to the complete 4D and 5D model created in the BIM environment.

3 RESULTS

Advances in technology have contributed to improved use of information model data. They have helped to improve pre-planning, the avoidance of geometric conflicts and also the control and management of the building throughout its life cycle. The term digitisation of a building represents the transfer of a real building into the virtual world through various technologies and processes [15], [16].

Digitization of the historical building

The digitization of the historic building was carried out in a specific historical church in the village of Rudník with the assistance of Doc. RNDr. Ján Kaňuk, PhD., from the Institute of Geography at Pavol Jozef Šafárik University. The entire digitization process consisted of three main procedural steps: scanning using a combined method, processing of point cloud data, and the creation of a 3D model of the structure.

A combined method of drone and laser scanning was used to digitize the church. The drone employed the method of oblique photogrammetry and was used to scan the church's roof. The scanning was facilitated using a DJI Inspire Z drone. The FARO Focus 3D × 130 laser scanner was used for scanning both the exterior and interior of the church from the ground.

The first drone flight was programmed to capture the surroundings of the church. The second flight was conducted manually and focused on the detailed capture of the church's roof and tower using high-resolution photographs. A total of 208 manually captured photographs was taken, with 128 photos captured using a 24 mm focal length lens and the remaining 80 photos using a 35 mm focal length lens. During the drone's flight around the church, it operated at altitudes ranging from 247 m to 297 m, covering an area of 0.0643 km².

After completing the oblique photogrammetry using the drone, the ground-based laser scanning process began. The first part of laser scanning involved capturing the complete exterior of the church. Prior to starting, parameters were set to meet the output requirements. The scanning duration was set to 3 minutes and 17 seconds, and colour scanning of the exterior was configured. The scanner created 360° scans approximately every 20 meters

at designated positions and where it was necessary for good scan alignment. The total number of scanning positions for the exterior was 12, and the total clean scanning time was 39 minutes and 24 seconds.

Once the exterior scan was completed, the interior scanning process was initiated. The original parameters were adjusted, reducing the scanning time to 1 minute and 52 seconds, and black and white scanning was configured for speed and due to the less complex interior. Positions were adjusted according to the layout of the church to minimize any blind spots in the final product. In larger interior spaces, the parameters were set back to their original values, but the output remained in black and white. The total clean scanning time for the interior was 27 minutes and 37 seconds.

To create the 3D model, Archicad 24 software was used, and the point cloud data was imported into it. Before starting the modelling process, floor heights, section lines, and the views were configured. Since the church consists of a single-nave space with a relatively high clear height, the project was adjusted accordingly before modelling to facilitate and improve the modelling process. The accuracy of creating the 3D model was verified by comparing it with the point cloud data in floor plans, sections, and 3D views. During this phase of modelling the church, the priority was not to create a material-accurate model but to create a geometrically precise 3D model of the church for obtaining project documentation.

For the subsequent renovation design, it was necessary to refine the 3D model (Fig. 4) and define individual constructions as sandwich elements. Thanks to this refinement of the individual parts, it is possible to assign information about time, cost, or, for example, fire safety data to each layer and construction.



Fig. 4 3D model - material composition specification (work of author).

Creating a 4D BIM model of the church renovation

Creating a construction schedule is important not only for efficient sequencing of processes but also for better allocation of financial resources. It also provides crucial information about the project's duration for the investor.

Microsoft Project Professional 2019 was used to create the construction schedule. To obtain unit labour costs for technological processes, CENKROS 4 software was used. A structure of all processes necessary for the restoration of the church was created in this programme. In addition to addressing the dismantling of old layers and the implementation of new parts, attention was also paid to auxiliary and preparatory processes related to scaffolding assembly and disassembly, debris removal, and site cleaning after the completion of construction work.

Calculating the total labour costs of processes required accurate input of material quantities. Refining the 3D model in Archicad 26 allowed the creation of a "Bill of Quantities" table. This table contained data on the length, area, and volume of materials, thanks to the precise modelling and definition of individual construction layers

according to the specified table. Since the church is processed in a BIM environment, all 2D components in the table are interactively linked to 3D elements of the model, and any changes are automatically updated.

Processing the fourth dimension of the Information Model involves linking time-related information with the 3D elements of the historical building model. This connection consists of three main steps: importing the IFC model of the historical building, creating or inserting the developed construction schedule, and defining the 3D elements related to each task. The fourth dimension was addressed using the Bexel Manager 21 programme, which supports the creation of the fourth and fifth dimensions of the BIM model.

After all the necessary settings, the programme was able to create a static visualization of the restoration of the historical building. This visualization showed the progress of work according to a pre-defined view without camera movement. After further adjustments, the programme highlighted critical path activities and their percentage of completion for the given day at the bottom of the visualization. In the figure (Fig. 5), you can see the progress of the church restoration stopped on May 22, 2023. On this day, scaffold assembly is 84.38% complete, removal of old coatings is 33.75% complete, and the entire project is 12.74% complete on that day. In addition to the percentage completion of processes, critical path activities are highlighted in red, and the visualization shows the status of processes in both 3D and percentage completion.

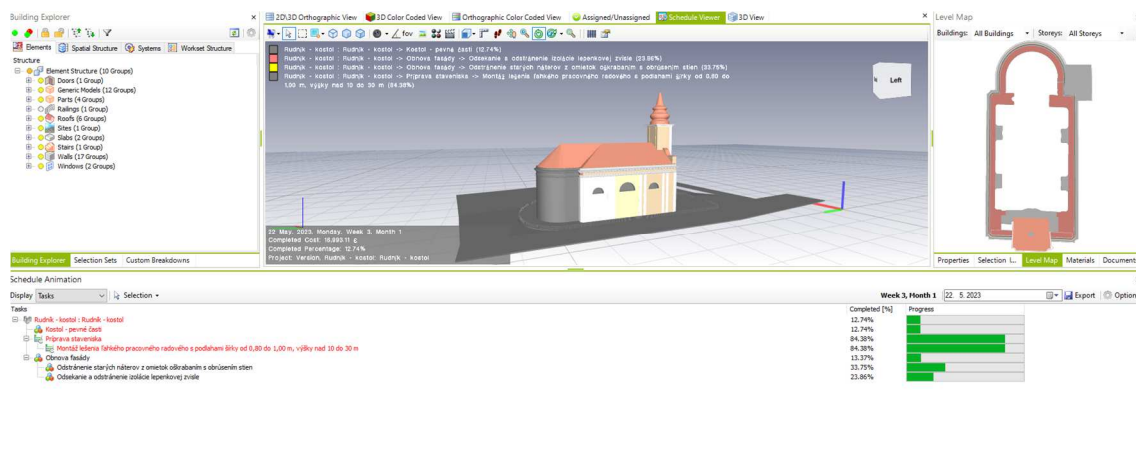


Fig. 5 4D visualization – May 22, 2023 (work of author).

Generating a 5D BIM model

When adding the fifth dimension to the model, the Bexel Manager 21 software was once again used. This software, in addition to supporting the fourth dimension, also facilitates the creation of the fifth dimension. A pre-established budget in the CENKROS 4 programme proved to be very helpful in this part, especially for obtaining unit costs when creating the time schedule.

After finalizing all adjustments to cost items, the Bexel Manager software can create a visualization of the restoration process, combining the fourth and fifth dimensions. You can stop the visualization on any day or select a specific date. When stopped, you can determine how much of the allocated costs should have been spent by that day, the percentage of completion for individual processes, and the total project cost. In addition to these pieces of information, the software can export the budget, making it easy to see how much of the total cost comprises expenses for machinery, materials, labour, and other costs.

The visualization of the historic church's restoration, as shown in the image (Fig. 6), is paused on June 16, 2023. From this visualization, you can gather information about the processes taking place on that day. For example, the process of "Cutting and removing vertical felt insulation" is completed at 65.91%, with incurred costs of this process up to June 16, 2023, totalling €49,971.06 out of the total process cost of €75,818.15. Apart from individual processes, you can also determine that the overall restoration progress for the historic building on June 16, 2023, is at 30.19%, with total costs incurred up to that date for the entire restoration amounting to €193,350.53. Above these 4D and 5D data, there's also a visualization of the progress of the restoration, allowing you to see the precise status of the restoration, the locations of various processes, which shots are being implemented, and how the restoration will look at that day. Such representation is highly beneficial, especially for investors, as it provides a clear understanding of the progression of processes and cost allocation over time.

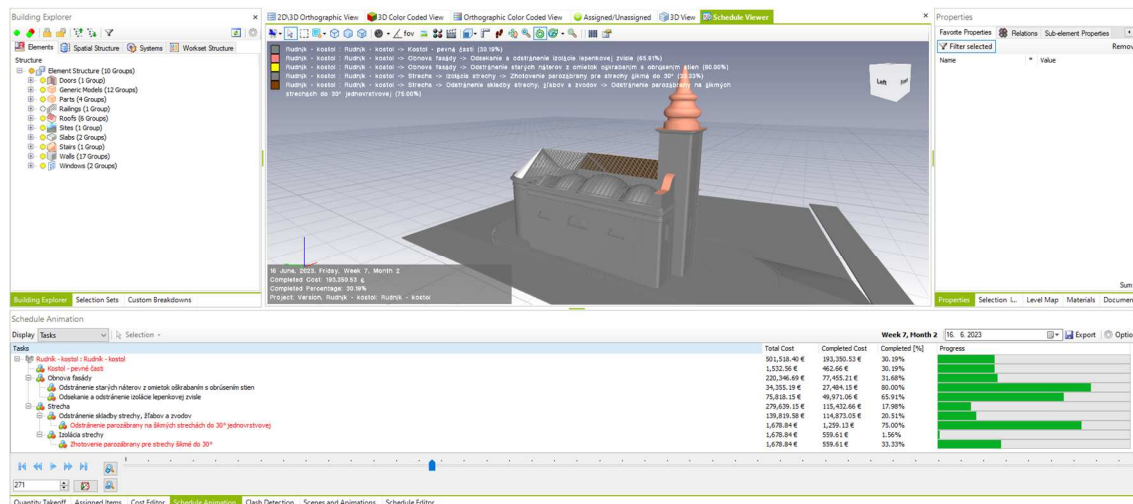


Fig. 6 4D and 5D visualization of the historic church building stopped on June 16, 2023 [work of author].

4 DISCUSSION

The utilization of a BIM model in the restoration design of a historic building consists of several steps (Fig. 7). The article describes the development methodology for effective and correct use of a BIM model in connection with the restoration of historical buildings and proves that the restoration of a historical building can be realized through BIM model, following and observing 6 basic steps. The article does not deal with the creation of data standardization, but examines whether the chosen methodology can effectively digitize the historical building and apply to this 3D representation of the building BIM logic such as the addition of a time parameter and the cost of renovation.

The first and most crucial step is the **clear definition of the restoration objectives**. Without a properly defined objective, the restoration process will be imprecise, error-prone, and, most importantly, inefficient. The accurate determination of restoration goals can be significantly aided by conducting preliminary surveys of the construction's condition. Such surveys may include preliminary and detailed examinations aimed at assessing moisture levels or the salinity of the structure. In addition to structural surveys, it is essential in historical buildings to conduct a restoration survey, which, besides providing an artistic and historical description, often includes a structural assessment of the condition of the construction and proposals for specific methods of preserving the cultural heritage.

Another part of the process is the **digitization of the historical building**. Historical buildings typically lack preserved project documentation, without which it is impossible to create a 3D model. Due to the irregular dimensions of historical structures and for rapid and efficient digitization, scanning can be carried out using a combined method, combining terrestrial scanning and drone technology. The acquired data can be processed using software such as Agisoft or FARO SCENE, and the resulting output in the form of a point cloud serves as the basis for the actual object modelling.

The next step is the actual **3D modelling** of the historical building. In this phase, the focus is primarily on the geometric accuracy of the object without specifying materials and sandwich constructions. 3D modelling can be carried out using construction software that supports point cloud data. Some of these programs include Archicad, Revit, or Allplan. The result is project documentation of the historical building, including floor plans, sections, and elevations.

The following part in utilizing the BIM model for the restoration design is **creating a timeline** for the restoration using software such as MS Project, Excel, or Contec. When creating the timeline, it is necessary to not only choose the individual processes correctly but also to accurately determine the volumes of the various layers of the structure. Working with a BIM model has the advantage of easily and precisely obtaining quantity take-offs for individual constructions without the need for complex and time-consuming calculations for irregularly shaped structures.

Once the schedule is created, the 3D model itself is refined. In this phase, it is necessary **to define the individual layers and material composition** for the parts undergoing restoration. This refinement of the 3D model aids in creating quantity take-offs for individual constructions and materials and also serves in the modelling of the fourth dimension of the BIM model.

The penultimate step involves **creating a 4D BIM model** of the historic structure. In this step, time is integrated with spatial elements. Using software like Bexel Manager, PlanRadar, or Autodesk Navisworks Manage, each modelled layer of construction is assigned a time unit. This allows for the creation of visualizations, such as a video recording of the restoration process of the historic building. Through this visualization, a more accurate understanding of the restoration process over time is achieved.

In the final step, the **5D BIM model of the historic building** is created, incorporating information about cost and expenses. Software tools like KrosBuild, Bexel Manager, or Linear enable the modelling of the fifth dimension.

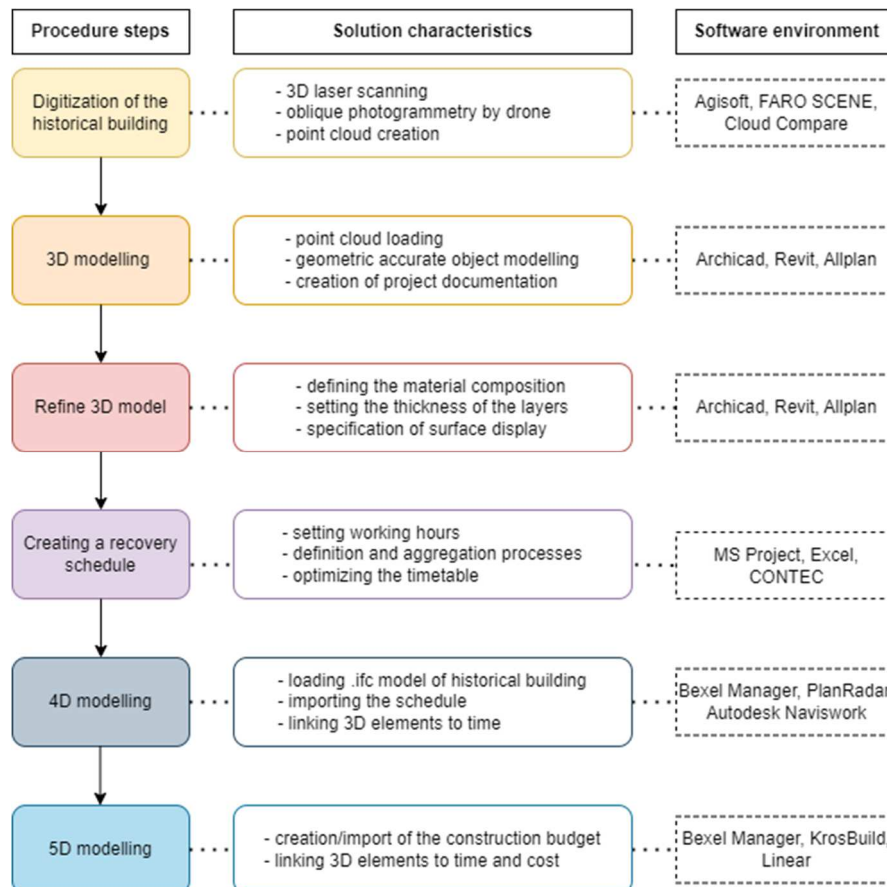


Fig. 7 Workflow steps for using a BIM model with a software solution [work of author].

5 CONCLUSION

The validity of the proposed methodology for using BIM models in the restoration of historical buildings has been confirmed through a specific case study of the church. The suggested methodology can indeed be applied to buildings and structures that lack complete project documentation or in cases where not all existing structural interventions have been recorded. This approach provides a systematic and efficient way to digitally capture, model, and manage historical building data, enabling more accurate restoration planning and execution while preserving the historical significance of the structure.

Preserving historical buildings is a challenging task due to their irregular shapes and unique characteristics. Digitalization plays a crucial role in obtaining precise geometric data for such structures. By creating layered models and utilizing them, it becomes easier to generate a bill of quantities, which significantly streamlines and expedites the project work. This approach ensures that the restoration and preservation efforts are based on accurate measurements and data, contributing to the successful conservation of historical buildings.

The methodology developed for historical buildings can also be applied to contemporary or modern structures. This is especially useful when the as-built documentation differs from the original design, additional modifications have been made over time, or there is no comprehensive record of alterations and reconstructions. Similarly, if a building has preserved project documentation but lacks a 3D model, the methodology can be adapted and applied

to create an accurate 3D model for various purposes, such as renovation, maintenance, or facility management. The versatility of the methodology makes it valuable for a wide range of architectural and construction projects.

Indeed, the implementation of a BIM (Building Information Modelling) model in the renovation process of historical buildings offers several advantages. One of the key benefits is the ability to acquire precise information about both the timeline and the cost of the entire renovation process.

By creating an information-rich BIM model, you can gain a clear understanding of how the renovation process will unfold over time. Additionally, because the BIM model links to cost data, you can reasonably estimate the expenses and how they will be allocated throughout the entire renovation duration. This level of insight is invaluable for project planning, budgeting, resource allocation, and tracking progress during the renovation of historical structures. It helps ensure that the project stays on schedule and within budget constraints.

On the other hand, a disadvantage may be the lack of familiarity with the software or the incompatibility of the individual selected software. It is from this point of view that it is necessary to take care before the very beginning to select the correct software environment in which the individual recovery steps will be processed.

In future phases, the BIM model can be extended to include other dimensions, where, for example, the sustainability of the building or facility management can be addressed. By adding other dimensions, the information model of the historic building will be complete and, if well linked or regularly updated, will represent a full-fledged digital twin of St. George's Church in Rudník.

Acknowledgement

This work was supported by the Slovak Research and Development Agency under the contract no. APVV-22-0576 “Research of digital technologies and building information modelling tools for designing and evaluating the sustainability parameters of building structures in the context of decarbonization and circular construction”. This paper presents partial research results of project KEGA 009TUKE-4/2022 “An interactive tool for designing a safe construction site in an immersive virtual reality” and project VEGA, grant number 1/0336/22 “Research on the effects of Lean Production/Lean Construction methods on increasing the efficiency of on-site and off-site construction technologies”.

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