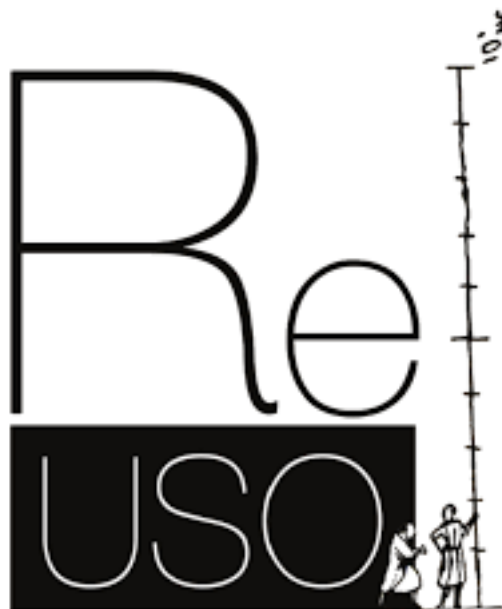


# Oportunidades que ofrece la tecnología digital para los problemas de documentación, seguimiento, uso y visualización del patrimonio arquitectónico y ambiental







Los cuadernos del ReUSO

**Oportunidades que ofrece la tecnología digital para  
los problemas de documentación, seguimiento, uso y  
visualización del patrimonio arquitectónico y ambiental**

*Dykinson, S.L.*

**Editores**

Adela Rueda Márquez de la Plata  
Pablo Alejandro Cruz Franco

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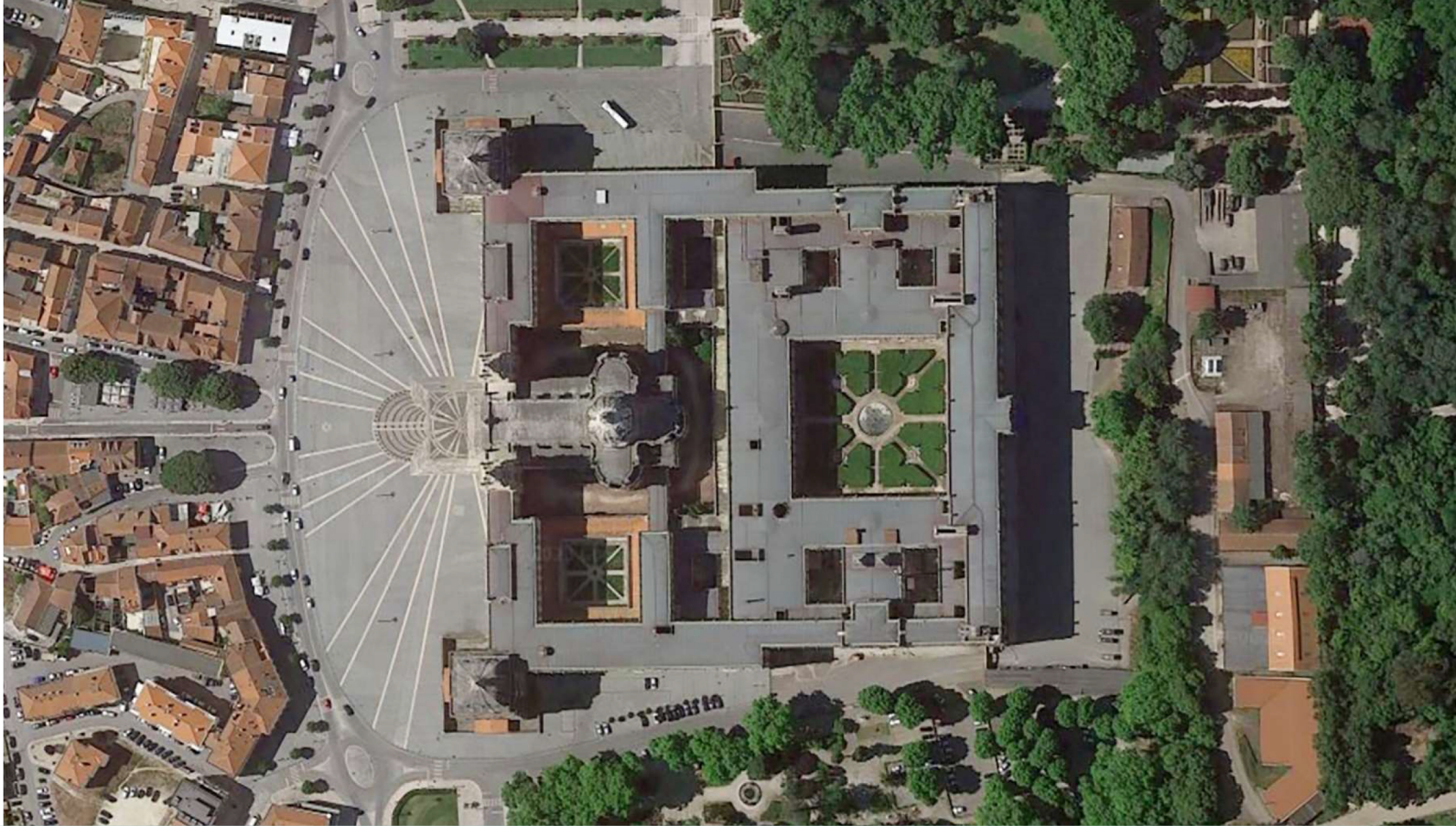
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### ABSTRACT

This chapter focuses on establishing best practices for converting as-built BIM models of historic buildings into BIM models suitable for 3D printing, with the aim of serving as tactile replicas for visually impaired people. By leveraging laser scanning technology, accurate 3D reality capture data are obtained, which constitute the foundation for creating the as-built BIM model and the subsequent 3D printing BIM model. Smart objects in BIM facilitate the efficient management of project components and their replacement, enabling updates to propagate throughout the model. The case study of the Palace of Mafra demonstrates the application of these practices. Guidelines for creating 3D printing models from BIM include defining 3D printing scale, specifying simplification levels, managing project phases, strengthening delicate elements, incorporating built-in joints, and selecting sustainable materials.



# ENHANCING UNDERSTANDING OF HERITAGE BUILDINGS THROUGH 3D PRINTED TACTILE MODELS IN BIM FOR PEOPLE WITH VISUAL IMPAIRMENTS

3D printing, Blind people, Scan-to-BIM, Heritage buildings, Palace of Mafra.

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## 1. Introduction.

3D tactile models are physical representations of objects or environments that are designed to be explored and understood through touch. These models are created using various technologies, including 3D printing and computer numerical control machining, to produce highly detailed and accurate replicas of real-world objects.

The primary purpose of 3D tactile models is to provide tactile access to visual information for individuals with visual impairments or other sensory disabilities. By feeling the physical features and surface of the model, blind or partially sighted people can gain a deeper understanding of the shape, size, and spatial relationships of the object or environment being represented [1], [2].

The crafting of an accurate 3D tactile model can be executed in different ways and is dependent on the dimensions of the original object, along with the scale and the final intricacy of the replica. The process typically begins by capturing the physical characteristics of the original object through direct measuring techniques such as manual measurements or creating a mold out of the object. Alternatively, indirect measuring methods like laser scanning or 3D photogrammetry can be used. These two latter techniques are great ways to capture complex shapes and details both for small and large objects, and can serve as a valid support if the final model is then resized with the help of computer numerical control machines or 3D printers.

The material is then shaped by sculpting or casting, or based on pre-programmed instructions. The final aspect of the replica takes into account factors like scale, level

of detail, properties of the material to be used, as well as surface roughness and finish according to the desired tactile response [3].

To enhance the tactile experience, additional elements can be incorporated into the model. For instance, braille labels, to provide additional information. These features help individuals navigate and interpret the model more effectively, expanding their understanding of the represented environment [4].

3D tactile models offer a powerful tool for accessibility, education, and engagement. By bridging the gap between visual information and tactile exploration, these models enable individuals with visual impairments to experience and appreciate the world in a multi-dimensional way [5].

## Tactile Models for low vision and blind people.

Despite the Unified English Braille notation provides guidelines for representing visual elements, including 3D objects (maps, diagrams, graphs, and illustrations) in a tactile format for individuals with visual impairments, and organizations such as the International Council on English Braille, the Braille Authority of North America, and Australian Braille Authority have developed guideline for the same purpose, there are not defined standards for the execution of tactile models.

Tactile models for individuals with visual impairments must be designed to be intuitive and user-oriented. For this

reason, it is important for the end-users to be involved in the decision-making process. They should define the level of detail required for representing the details that can be felt by touch, namely the raised elements that represent the various features, textures, and details of the object. The height and depth of these surfaces must be carefully designed to provide a clear distinction and accurate representation of the tactile information.

In the case of large and complex objects, like buildings for instance, it may be necessary to simplify the ornamentation or even remove redundant elements from the model to enhance clarity and optimize the tactile experience. Size and scale considerations are also essential, allowing for comfortable handle and exploration. Models can be scaled down to a manageable size, ensuring that individuals can effortlessly comprehend the model's intricacies.

Other relevant aspects to consider for a good result are linked to the clear contrast and differentiation of the model parts. Tactile models utilize contrasting colours, textures, or materials to differentiate between elements or areas. This contrast helps individuals with visual impairments to distinguish between parts and understand the spatial relationships within the model. To ensure a favourable outcome, it is essential to consult with the final-users themselves for a tailored and optimal tactile experience. It is important to recognize that each project is unique, and there are no pre-defined standards for every scenario.

On the other hand, it is a requirement that 3D representation be uniform across all areas. This principle mandates that project specifications be consistently applied, ensuring that the level of detail and degree of simplification remain constant throughout the entire model. Repetitive elements should be depicted uniformly as well. Furthermore, when multiple models are displayed within a single exhibition or location, they all should maintain consistency in scale, level of detail, simplification, and material selection [6].

The choice on the material is usually dependent by the sculpting method or the type of machine that will realise the

model and can affect accuracy and surface smoothness. In any case, tactile models must be constructed using durable materials to withstand repeated touch and exploration, ensuring that the model retains its tactile features and structural integrity over time.

The layout and organization of the model should be logical and easy to navigate, allowing users to explore the model independently. For this reason, model descriptions can be provided by incorporate textual information in braille format onto the support or directly on the model surface. These labels usually provide object names, or explanations, enabling blind individuals to access the relevant information by touch.

Tactile models can be complemented by other sensory elements to provide extra context, for example, audio guides or verbal descriptions [6].

## 1.2. 3D printing architectural models.

3D printing is a rapid prototyping method that creates the final model by layering materials using additive manufacturing process. The printer extrudes molten material filaments to form each layer.

Fabricating tactile architectural models with 3D printing is not just an easy and cheap process, it's an initiative of great value. Specifically tailored for visually impaired or blind individuals, these tactile models serve as tangible gateways to understanding and experiencing the contours and layouts of buildings, landmarks, or other architectural wonders. These models transform the abstract into the concrete, granting individuals access to a world they might otherwise struggle to explore.

In the past, these kind of models were made usually in bronze (Fig.1), by lost-wax casting the metal in the mold of the model. Traditional sculpting techniques were required,





*Figure 1: Florence, Piazza della Repubblica. Bronze model of Florence city centre, Unesco World Heritage site.*

possible to execute the 3D printing of building and even city replicas from our desks.

The primary and most well-known technology in 3D printing is the Fused Deposition Modeling (FDM), also known as Fused Filament Fabrication (FFF). S. Scott Crump developed FDM in the late '80s, and it was commercialized by Stratasys in 1990. In 2005, Professor Adrian Bowyer initiated the RepRap project, the global movement behind self-replicating and open-source 3D printers that share the same name [8]. Thanks to that, today, cheap and efficient 3D printers can be easily used at home and do not require a high skillset for their operation. What is required is a primary attention on the printing process, and on some measures to apply during the modelling phase of the building.

The fundamental elements for FDM devices are essentially three: a print bed, on which the piece is printed, a filament spool that serves as the printing material, and an extrusion head. The printing process happens at high temperatures, superior to 160° C, and the nozzle moves and lays the extruded thermoplastic material on the print bed, where it

cools and solidifies, following the x, y coordinates that the computer communicates. The extension of the print plate and the distance between it and the nozzle determine the maximum size of the printed piece. Due to these operating limitations, the model often needs to be split into sub-elements to be assembled and glued together after the 3D printing.

The accuracy and the quality of a printer are related to nozzle size. The diameter of the nozzle frequently employed in common 3D printers is 0.4 mm. As the nozzle size increase, the printing time decrease. It is a common habit to switch nozzle for a bigger one to speed up the printing process. But, in the case of tactile model, it is highly suggested to use always the same nozzle diameter in order to do not have different textures on the surface model and to avoid interferences during the touch experience. This precaution is not needed if the 3D printed model goes through a finishing process in which its surface gets cleaned, polished, and painted.

The materials used for 3D printing tactile models are diverse, but they all need to possess specific properties to ensure the models are safe, durable, and useful. Adhere to the safety standards is a part of the process for the creation of 3D tactile model to ensure that the materials used are non-toxic. Also, all edges and points should be rounded and smoothed to ensure they are safe to touch. The common materials used are reported in table below (Fig.2)

The 3d printing is always preceded by two preliminary stages: the process of modelling, and the optimization of the model for the 3d printing. The design modelling of a building is done at the computer using usually a Computer-Aided Design (CAD) software.

MATERIAL	DESCRIPTION	PRINTING EASE	STRENGTH AND DURABILITY	COST (1 KG SPOOL)
PLA (Polylactic Acid)	Made from renewable resources like corn starch or sugarcane. Biodegradable, non-toxic, and easy to work with. Suitable for detailed models. However, less robust and can degrade over time.	Easy	Lower	€20 - €50
ABS (Acrylonitrile Butadiene Styrene)	Stronger and more durable than PLA. Requires good ventilation due to fumes when heated. Suitable for frequently handled models. More challenging to print with.	Moderate	Higher	€20 - €50
PETG (Polyethylene Terephthalate Glycol)	Combines ease of printing like PLA with strength and durability like ABS. More flexible than PLA and ABS. Suitable for models subject to rough handling.	Easy	Higher	€25 - €60
TPU (Thermoplastic Polyurethane)	Highly flexible and durable material. Suitable for models that need to withstand extensive handling. More difficult to print with.	Difficult	Higher	€30 - €70
ASA (Acrylonitrile Styrene Acrylate)	Similar to ABS in strength and durability, with better weather resistance. Suitable for outdoor or UV-exposed environments. More expensive due to specialty filament.	Moderate	Higher	€30 - €70

Figure 2. Common materials used in 3D printing

Several software tools can be used to model buildings for 3D printing. But they must ensure the exportability of the file in a format compatible with the 3D printer, usually STL or OBJ. If the software is used to replicate an existing model, the availability of point cloud data import functionality within the working environment must be verified. Software such as AutoCAD, Rhino, Revit, and Fusion 360 offer this essential feature.

Following the design phase, wherein the 3D model is created, it is necessary to process and optimize the model using specialized software known as a “slicer”. A slicer software tools can handle tasks like optimizing the model for print speed or quality, generating supports for overhanging parts, and splitting the model into layers for printing. Some of the most popular slicer software options that can help to prepare and optimize the 3D model for 3D printing are: Cura, Slic3r, Simplify3D, PrusaSlicer, and IdeaMaker<sup>1</sup>. The slicer takes the 3D model and “slices” it into many thin layers, then translates each layer into G-code<sup>2</sup> so the printer knows how to produce each one.

Typically, the slicer converts the models into two distinct but continuous components: an exterior solid shell and

an interior infill structure. The interior infill structure is frequently designed to be partially hollow, and filled with patterns such as honeycombs, gyroids, triangles, grids and complex curved structures. This is done for several reasons:

- Material Conservation: 3D printing a completely solid object would use a lot of filament material. By using infill, the amount of material used is significantly reduced, without greatly affecting the overall strength.
- Time Efficiency: Printing solid parts would also significantly increase the time it takes to print an object. Infill patterns allow prints to be completed faster.
- Structural Integrity: The infill patterns provide a good balance between strength and material use.
- Weight Reduction: Parts with infill are also lighter than solid parts.

The infill percentage and the thickness of the exterior shell are values chosen by the operator. Another critical parameter that can be set on the slicer is the layer height, which can be adjusted based on the nozzle size, and is recommended to be set between ¼ and ¾ of the nozzle diameter. The

software provides also a feature to generate supports, which are temporary structures made of the same material as the printed object. These supports serve as “scaffoldings” to hold up protruding or overhanging parts during the printing process. Once the printing is finished, the supports need to be carefully removed. This operation can be leaving behind small scars on the object’s surface, which can be smoothed out by sanding the material in excess to achieve a desired finish.

## 2. The role of BIM

With the increasing adoption of BIM worldwide, there will be a rise in BIM models for historic and heritage buildings in the coming years and it should be thought a possible reuse of such complex models.

A key challenge addressed in this chapter is to create the 3D printing BIM model by converting the as-built BIM model [8] while adhering to simplification rules. The goal is to integrate an as-built BIM model and a 3D printing BIM model, both derived from laser scanning data [9] into a single BIM project file.

Creating as-built BIM models for historic buildings is a labour-intensive and cost-effective process that requires expertise in working with point clouds, BIM components, and adhering to BIM standards. Specialized training is necessary to carry out these operations effectively. Reusing existing BIM models of buildings to create or convert them into tactile 3D printed models provides an opportunity to repurpose these models.

BIM utilizes smart objects referred to as “families” to enable efficient management of project components. Any modifications made to a family automatically update all instances throughout the project. In this research, this feature is utilized to streamline the conversion process.

## 3.1. Methodology

This research focuses on establishing best practices for converting as-built BIM models of existing historic buildings into BIM models suitable for 3D printing of tactile models.

Starting from the survey-scan-to-BIM model, a duplicate of the model is created on which to apply the degree of simplification for the 3D printing.

Usually walls and roof families can be kept as they are, since their surface is usually smooth and does not need any simplification. But, all the other families as windows, door, frames, etc. must be adapted for the 3D printing.

Two main principles emphasize the idea of adapting and modifying existing BIM families for new purposes, showcasing the potential for resourcefulness and innovation within BIM, which are:

- Repurposing an existing BIM family, which means modifying it or utilizing it in a different context or for a different purpose. It highlights the ability to repurpose existing resources rather than creating new ones from scratch.
- Refactoring an existing BIM family, which means signifying the process of restructuring or reorganizing a BIM family to better suit a new purpose. It implies making changes to the family’s parameters, geometry, or other elements, while ensuring its functionality and performance.

By utilizing these principles, we can take an existing as-built BIM model and convert it into a BIM model specifically tailored for 3D printing. This approach allows us to leverage the fact that common elements can be effectively reused.

Once the conversion to a BIM model for 3D printing is complete, then it can be exported to the slicer where it would get its optimization for the 3D printing. Only then the G-Code gets exported and the 3D printing executed.

Eventually, if needed, the pieces that compose the model have to get assembled, glued together and treated with finishing products (Fig.3).

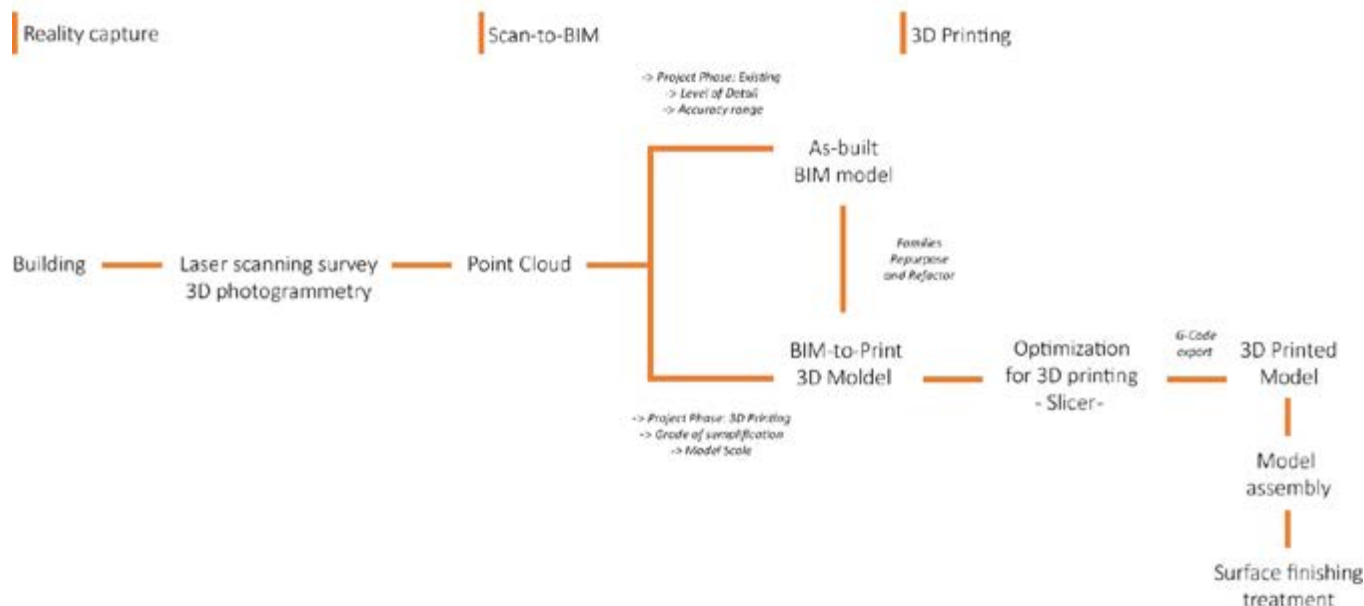


Figure 3. Project Workflow

### 3.2. Case study: The Palace of Maфра

The initial dataset for this research utilized a point cloud of the Palace of Maфра<sup>3</sup>, obtained from a 2017 laser scanning survey conducted collaboratively by the Direção Geral do Património Cultural (DGPC) and the Faculty of Architecture of the University of Lisbon (FAUL).

The DGPC has recently invested in accessibility and inclusion for museums, monuments, and world heritage sites under its administration. As part of this effort, tactile models of the Palace of Maфра, the Monastery of Alcobaça, the Monastery of Batalha, Convent of Christ in Tomar (all classified as world heritage sites), and the Museu Nacional Machado de Castro in Coimbra are now available for visitors who are blind or have low vision. These models are accompanied by English and

Braille descriptions, audio guides, and sign language videos. The FAUL was involved in the modeling (in CAD) and printing of these monuments as part of the “Accessible and Inclusive Communication” project [10]. The parameters used for 3D printing the aforementioned Portuguese monuments were applied to this research, mainly the chosen representation scale and simplification criteria, which were defined and validated jointly with ACAPO (Associação dos Cegos e Amblíopes de Portugal)<sup>4</sup>.

The point cloud data, capturing the exterior facades of the building, was used to create an as-built model of the southwest area (tower and adjacent facades) using the Scan-to-BIM process. The research aimed to address the challenge of creating a LOD 250 as-built BIM model of the Palace’s exterior, followed by a second model optimized for 3D printing by leveraging the characteristics of the first model. This approach simulated a likely scenario where scan-to-BIM models are reused for creating 3D printed tactile models of heritage buildings, offering an additional purpose for these

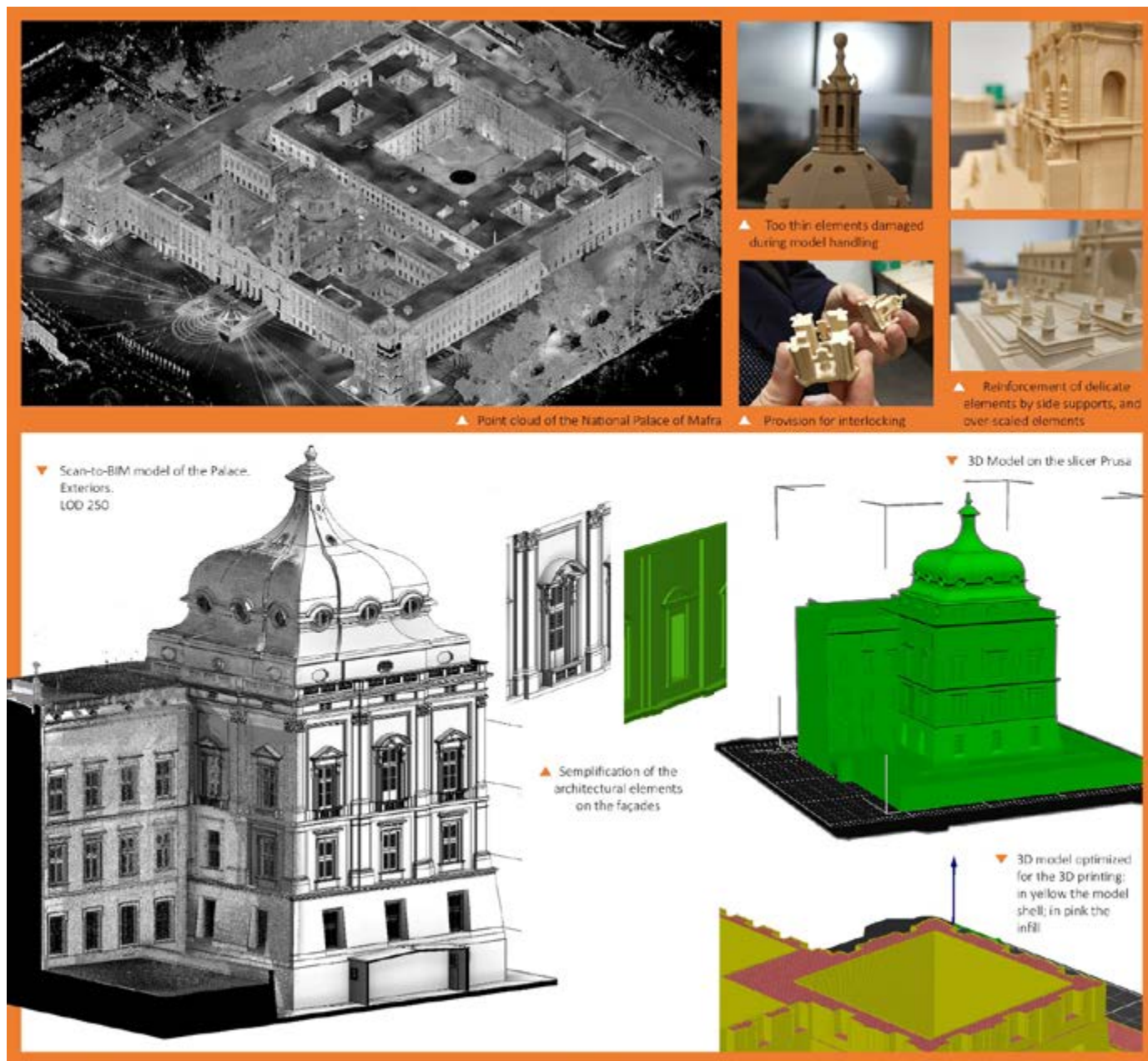


Figura 4. 3D printing BIM model of the Palace of Mafra.



complex and time-consuming Scan-to-BIM models.

As per BIM standard requisite, as-built BIM models must adhere to detailed specifications included in the accompanying BIM project documents, accurately describing the required level of detail and accuracy for the project. Once the as-built model was complete following the specifications, a duplicate was created for its conversion into a 3D printing BIM model. The new 3D printing model had to coexist without any ambiguity within the same project file as the as-built model. To achieve this, the 3D printing model had to possess the following characteristics:

- Recognisability to avoid equivocation with the existing BIM model.
- Compliance with BIM standards for naming conventions.
- Non-interference and avoidance of clashes with existing and future models.
- Configurable visibility to be turned off when not in use.

To address these requirements, the project structure underwent adjustments. A new workset and a new construction phase named “3D printing” were created within the same project. This new phase hosted the version of the model specifically designed for 3D printing, along with its associated families. By implementing this structure, the 3D printing model could be easily toggled on and off as needed, preventing interactions and clashes with other project phases or elements.

To ensure the distinguishability of the pieces for the 3D printing within the project, a new material with a distinct colour (different from the default grey colour, namely green colour) was created and applied to the 3D printing model.

Additionally, code naming was applied to the adapted and refactored families for the 3D printing model, enabling their recognition within the project. Following BIM standardization, the family names incorporated: the project name; the “3D printing” tag; the family characteristic description; the dimensions; and the version number,

facilitating identification and organization.

The representation process for this project adopted a 1:300 scale, allowing for easy handling of the entire height of the palace. This scale also facilitated effective simplification of the decorative elements on the facades.

To achieve simplification, profile frames throughout the facade were modified. Small curves were rectified, and any moldings smaller than 10 cm were removed.

Regarding all the windows in the project, all the frames on the window panel were deleted, as well as any glass separators, leaving only a window aperture on the wall. However, the window aperture, as it was per the default window families, was replaced with a void extrusion. The depth dimension of this extrusion was parameterized to allow for adjustments in the depth of the void in the wall, based on the user’s request - by simply changing parameter value. The windows designed this way, did not cut through the wall but created a recessed area in the wall itself, generating high shaded and contrast areas on the façades. This intentional design element enhanced readability for individuals with low vision. The same principle was applied to the door families.

Any building cornices at each floor level, balcony slabs, and protruding elements required a continuous bottom support whit triangular section to enable their printing.

Roof and walls were kept as per the As-built BIM model.

Built-in joints were modeled to connect pieces of the model that could not be printed as a single block.

Unlike traditional CAD models, which are typically solid blocks, the BIM model was constructed with walls that created an internal cavity within the building model. We realized this necessitated the addition of internal solid volume in the BIM stage since slicer applied the infill only to solid areas.

The BIM model was exported from BIM software and converted to the STL format for use in PrusaSlicer. The maximum printing dimensions of 250x210x210 mm were taken into account – considering the features of the

Prusa i3 Mk3S+ printer being used – for the chunks to be printed.

## 4. Results: guidelines for 3D Printing Tactile Models in BIM

To ensure the successful creation of a 3D printing model from an existing BIM model, it is suggested to follow these best practices:

1. Define the printing scale clearly to ensure accurate representation of the model.
2. Specify the level of simplification required, providing a detailed description of the desired appearance. If necessary, use examples for clarity.
3. Prepare a comprehensive list of elements that need to be removed (small cornices, frames, capitals, door and window panels details, etc..).
4. Identify families that should be refactored using new simplified profiles and elements.
5. Set the same material colour to all families to be 3D printed.
6. Set project construction phases and manage the phase visualization filter in order to see the As-built BIM model “OR” the 3Dprinting BIM model.
7. Strengthen delicate elements by increasing their dimensions or modifying their shape. Architectural details like pinnacles and gargoyles are prone to wear and tear, especially due to human touch. To address this, consider incorporating side support elements or enlarging the scale of small objects. Triangular side-structures can be used as additional support, ensuring the longevity of these intricate features.
8. Incorporate connecting joints into the model if its extensions need to be printed in separate chunks. These joints should be designed and integrated into the model. Box joints are ideal for vertical connections, while dovetail joints work well for side-by-side connections. These joints, commonly used in woodworking, rely on the frictional force between two mating parts to provide a strong bond.
9. Include built-in recesses in the model to accommodate the insertion of nuts and bolts. These recesses are useful when attaching the 3D printed model to a support stand for display at exhibitions.
10. Select a sustainable material for printing, considering factors such as hardness and durability. This choice will ensure the longevity of the model.
11. Choose an appropriate colour that suits the preferences of the end-user. Keep in mind that some visually impaired individuals may have colour perception, so it's essential to consider their needs as well.
12. If necessary, consider 3D printing a Braille description plaque to provide accessibility for individuals who are blind or visually impaired.

## 5. Conclusions

BIM is becoming the main tool for managing process in the AEC industry. It is a cost and labour intense process, and new ways to exploit such rich and complex model are required. By merging the 3D printing model and the as-built model within a single project file, we can leverage the strengths of each model while promoting the reusability of common elements. Through careful consideration of guidelines, reinforcement techniques, and usability factors, we can achieve remarkable outcomes in terms of heritage accessibility to all. This research, while focusing on the technical aspects of integrating BIM models for 3D printing, it has equally addressed importance to considerations on

3D printed usability and accessibility. The resulting printed model should cater to tactile interpretation, enabling individuals with visual impairments or other sensory

disabilities to engage with and appreciate the architectural design.

## Notes

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1. *Cura*, developed by *Ultimaker*, is open-source, and slices the 3D model into layers and generates the G-code necessary for the 3D printer; *Slic3r* is another open-source slicer program that's quite popular. It has a lot of advanced options, allowing for a high degree of control over the 3D print; *Simplify3D* is a commercial slicer software that's known for its comprehensive features and ease of use. It allows the user to control a wide range of variables, making it suitable for more complex 3D prints; *PrusaSlicer* was initially designed for the *Prusa* line of printers, this open-source software is now compatible with most FDM printers. It's highly customizable and provides detailed control over the printing parameters; *IdeaMaker*, developed by Raise3D, is a powerful slicing software with advanced features like a variety of infill options.
2. G-code is a language used to instruct computerized machine tools how to make objects and it is often used in manufacturing and 3D printing.
3. The laser scanning survey involved the exterior part of the building, and it was made by Prof. Luís Mateus and Prof. Victor Ferreira from the FAUL.
4. The 3D printing of the monuments and their details for the DGPC was coordinated and executed by Prof. Victor Ferreira and Prof. Luís Mateus

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