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Comprehensive design of the 3D printing process for architectural models. A case study: the medieval walled enclosure of Priego De Cordoba (E1:200)

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Abstract

Nowadays, an object can be viewed both physically and virtually. In both cases, the visualization process consists in a continuous variation of the observer's perspective. When looking at objects, visual interactivity is achieved by the tandem formed by human vision and the position of the observer. 3D technology allows the viewer to delve into this aspect: starting from a virtual reconstruction. It is possible to go from the virtual 3D reconstruction of a model shown on a display to a real element materialized by means of a scale model or prototype. The innovation of this research lies in the development of an efficient method for printing 3D models, with a specific emphasis on material and time savings. This study aims to obtain the three-dimensional physical model of the walled enclosure of the city of Priego de Córdoba in the Middle Ages, at its time of greatest historical development, i.e., in the late 15th century. To this end, 3D printing technology was applied, which is an innovative method for the realization of architectural scale models. The performance of 3D printers, with different printing formats, was evaluated in terms of efficiency and quality of the architectural scale models. Our theoretical assumption showed that material saving is determined by the orography slopes of the model. Obtaining slopes with values in the range of 1–5%, a large format printer is the most suitable option; in the range of 5–15%, the medium format printer is recommended; and, for a slope greater than 15%, the small format printer should be used.

Keywords 3D printer · Interactive scale model · 3D modeling · Virtual reconstruction · Fuse Deposition Modeling (FDM) · Polylactic Acid (PLA) · Rapid prototyping

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1 Introduction

The first evidence of the existence of scale models dates to the Egyptian era (Egyptian art), when they had a ritual and domestic character. In Roman times, they were used as a sign of power and coexisted with the representation of scale plans that were used in war conflicts[1], since they allowed greater control of space as a strategy of territorial domination. In the Renaissance, the working model appeared for the first time and as a means of negotiation, although it was not until the Napoleonic era that a more detailed form of cartographic representation of the terrain emerged [1]. There is the model of Rome made by French military engineers representing the siege of Rome in 1849 as a significant example. In general, it is common to resort to scale representation for the visualization and marking of a location from a dominant perspective. Since its inception, humans have attempted to copy the reality closest to them, and, under this concept, the first three-dimensional models arose, imitating the architecture of the time as objects of cult and adoration.

In the ever-evolving landscape of modern technology, 3D modeling and Fused Deposition Modeling (FDM[2]) printing have emerged as revolutionary processes, reshaping the way to design, to create prototype, and manufacture objects. These technologies have transcended traditional manufacturing methods, offering unprecedented flexibility, creativity, and efficiency in bringing ideas to life. Nowadays scale models are used in numerous fields [2]. A new digital stream associated with 3D modeling has been configured for the implementation of scale prototypes. There is a great variety of technologies used for the manufacture of prototypes [3], and this study focuses on 3D printing.

Some important definitions to better understand the research are:

1. *3D modeling*: a digital technique that allows creating three-dimensional representations of objects or scenes using specialized software.
2. FDM *Printing Technology*: complementing the prowess of 3D modeling with Fused Deposition Modeling (FDM). This process involves layer-by-layer extrusion of thermoplastic materials, such as Polylactic Acid (PLA) or Acrylonitrile Butadiene Styrene (ABS), to construct a physical object based on a digital model.

This technique makes it possible to physically build a virtual 3D model using additive manufacturing layer by layer via the deposition of molten material. Therefore, this research addresses the physical transformation of a scale model from the virtual reconstruction of a 3D model, providing it with interactive functions that allow using it in both tourism and education. This research consists in proposing a method that values the realization of an interactive model by means of 3D virtual modeling and an optimized FDM printing technology. Making a state of the question that analyzes the aforementioned concepts was fundamental for the understanding of the study, in which both technologies converge. Any virtual or digital reconstruction can be printed in 3D [4]. The synergy between 3D modeling and FDM printing is evident in their collective ability to bridge the gap between imagination and reality.

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[1] For military purposes, the Romans knew how to carry out different types of cartography: the itineraria scripta or adnotata (with simple annotations) and the itineraria picta (much more realistic, colored and the morphology of the relief and the landscape was indicated).

[2] In 1988, Scott Crump unveiled the first fused material deposition printers FDM (Fused Deposition Modeling). Later, in 1990, they were marketed by co-founder Stratasys (USA).

2 State of the art

Computer-aided design began to be used industrially in the 1970 and 1980 s, while the development of the first 3D printing technologies dates back to the mid-1980s [5]. Their greatest evolution took place in the following decade, coinciding with the evolution of computer equipment, becoming more powerful, easier to handle and more affordable. A 3D model can be represented both on the screen as a two-dimensional image or as a physical object through a 3D printer.

Numerous authors have valued cultural heritage through its graphic representation and even making use of new innovative representation technologies [6–11]. Likewise, it is worth mentioning previous research related to printing 3D objects, such as the study of the reintegration case through 3D printing of a digital 3D model of a Roman cornice at the Castulo Archaeological site in Linares [12]. However, few studies have been focussed on optimizing the process of printing the created 3D models, especially using interactive resources. Making an interactive model based on a virtual model is typical of the current digital age [13–15]. Constructing a physical and palpable object such as a scale model allows people to access a virtual world through a mobile device and virtual reality goggles. Everything is possible thanks to the previous work conducted on 3D modeling[3].

As a relevant fact, it should be noted that 3D printing technology serves as a link between 3D modeling in the first phase and the virtual tour as an interactive tool in the final part. A 3D printer is a machine capable of materializing a virtual reconstruction from a digital file, as a new object that did not exist before. In 1980, Charles W. Hull, a leading inventor in the field of ion optics, laid the foundations for the first 3D printing method, stereolithography[4] (USA Patent No. 4,575,330 1986). Later, in 1989, FDM technology was developed by S. Scott Crump, consisting in modeling by deposition of molten material, and it was commercialized in 1990 by the company Stratasys, which was co-founded by him [16]. Nowadays, 3D printing is one of the markets with the greatest future expectations worldwide, which was highlighted by the COVID-19 pandemic [17]. The vulnerability shown by the medical sector, among other sectors, was present in our day-to-day lives. The absence of the necessary equipment to deal with the spread of the virus triggered the solidarity of both institutions and citizens, who found in 3D printing technology the perfect tool to cover the manufacture of this medical equipment. Face shields, emergency equipment and ventilators were manufactured, and manufacturers became service providers for the health sector [18].

As in other cases it is possible to act, for example, in the educational field [19], making historical aspects known through a 3D printed model as well as teaching both students and teachers the possibilities of this technology, which allows converting a virtual model into a physical model for support during teaching [20]. One example is the performance of various activities in the IES Fernando III El Santo secondary school in Priego de Córdoba (Spain), where, with the participation of its teaching staff associated with the subject of Geography and History, disruptive technologies were used to carry out different interactive

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[3] It consists in creating a mathematical representation of surfaces using geometry.

[4] Rapid prototype system through which solid three-dimensional models are obtained by processing data organized in a *.stl file.

activities in order to discover the potential of a military defensive structure of the fifteenth century[5].

3 Research context and preparation

The participation of a local administration that is committed to the recovery of its rich and varied architectural heritage is needed to carry out the 3D modeling and printing of the walled enclosure. Likewise, extensive archaeological documentation complemented by various written historical sources including planimetry, as well as graphic elements of interest, are also required. Only in this way can the proposal have a scientific nature, and its layout, design and volumetry will be justified, without prejudice to future corrections of the model based on the contribution of new data. In this context, the Tourism Area of the Council of Priego de Córdoba, agreed to participate. The documentation provided by the Municipal Archeology Service [Municipal Historical Museum], was available, and it was crucial to undertake this work. This Service, since its creation in 1989, has carried out key archaeological interventions for our reconstruction proposal, also contextualized in conventional historical sources.

The elements of greater scope that have helped to consolidate the recreation proposal are:

1. Archaeological analysis of the preserved emerging structures, both in the castle and in the walled enclosure, with the latter being limited almost exclusively to the rampart sector. The conventional archaeological record was essencial contribution, resulting from numerous archaeological interventions. The accumulated scientific bibliography is significant and essential information was taken from it [21–31]. Numerous unpublished or partially published data were also used.
2. Documentary data recovered from the Capitular Acts preserved in the Municipal Historical Archive that indirectly inform about the characteristics and layout of the walls, as well as their historical evolution.
3. Analysis of historical graphic documentation, such as:

    3.1 Anonymous panoramic view of Priego de Córdoba from the early 19th century, painted in oil, preserved in the Ducal Archive of Medinaceli [32]. This painting has valuable contributions on the towers of the Tajo del Adarve and surroundings of the current Puerta del Sol (Ochavada Tower).

    3.2 Engraving with a representation of the breast wall and battlements of the Tajo del Adarve of Priego de Córdoba dated 1762 [33]. It confirms the use in this sector of battlements crowned with pyramidons, or four-sided coping.

4. Municipal Historical Museum. This archaeological museum in Priego de Córdoba preserves one of the pyramidons that crowned the battlements in the rampart sector. It is a chance finding that comes from the base of the Tajo del Adarve.
5. Historiographical and bibliographical mock-up. Carried out with the aim of arguing specific proposals or filling in the spaces for which there was not enough information.

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[5] Activities included in the TFM "Application of the Flipped Classroom Method and use of VR Resources in the Educational Field. Case Study: I.E.S. Fernando III in Priego de Córdoba" carried out by Diego Francisco García Molina.

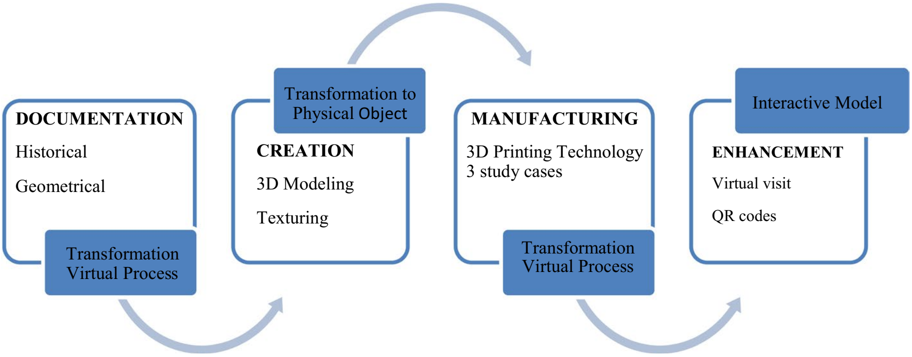

Fig. 1 Phases for the realization of an interactive architectural model

The interactive architectural model constitutes the culmination of a previous work initiated in the last ten years in Priego de Córdoba. This prior work, in which numerous cutting-edge techniques were implemented, provided the archaeological and historical geometric documentation of the walled enclosure of medieval Priego de Córdoba (madinat Baguh) at the end of the 15th century, for instance, a high-definition topographic survey with a terrestrial laser scanner, aerial photogrammetry with a drone in the screed of the ramparts and structured light in a pyramidal merlon [34, 35]. The latest restoration work allowed the castle to recover a very significant part of its authentic appearance in the 15th century [36].

4 Objectives

The aim of this research was to comprehensively develop the 3D printing process for architectural models, tackling these specific objectives:

1. To identify an efficient method for printing 3D architectural models, with a specific focus on material and time savings.
2. To study the print parameter settings to obtain optimal print quality.
3. To highpoint and enhance the value of the walled enclosure of Priego de Córdoba

5 Methodology

5.1 Process workflow

There are numerous studies where the research base is developed around a virtual reconstruction [15, 37]. Generally, the workflow is divided into phases, developed by a multidisciplinary team, consisting of documentation, data collection in the field, and office work, which provides different results. In the same way, the enhancement was carried out through information panels, videos and even interactive tools [38].

This research attempted to go further and highlights the enhancement of the 3D model by moving from a digital file to a physical and palpable object through an architectural scale model equipped with interactive resources. This fact allows going from a virtual reconstruction to a physical reconstruction thanks to the appearance of additive manufacturing and 3D printing technologies. The method proposed in this study broadly reflects the different phases that make up the work: documentation, creation of the three-dimensional model, manufacture of the model, and enhancement of the architectural element through the implementation of interactive tools in the scale model itself (Fig. 1).

The methodology focuses its interest on the manufacture of the model using 3D printing technology with FDM, since it represents the innovative aspect of the work. The virtual scale model can be manufactured in a practical and efficient way; this requires specific equipment that provides the largest printing volume and surely saves on gross manufacturing time[6], which encompasses the entire process. The net time, dedicated exclusively to the printing of a piece, is different. The net time is that considered and studied by this proposed method. However, the gross print time is unpredictable, since it increases notably with the increase in the number of pieces. Although this fact may seem like a drawback, one of the goals of this research was to save material.

To achieve this, authors developed the following steps during the manufacturing phase:

1. Choice of 3D printing technology and material promoting the use of environmentally friendly materials.
2. Determination of the manufacturing scale based on the 0.2 mm display standard, checking the representation and display of those small elements that are part of the model.
3. Estimation of material savings based on the topography of the terrain of the scale model (calculation of the average slope of the longitudinal and transversal section).
4. Choice of equipment for 3D printing that determines the number of pieces that make up the model.
5. Delimitation of the exterior and interior area of the scale model (parts with and without material savings, respectively).
6. Results: volume reduction of the parts depending on the type of 3D printer used and, consequently, percentage material savings.
7. 3D printing: Choice of equipment and configuration of parameters.
8. Finishes and final presentation of the scale model.

A comparison using three printers with different printing formats was performed to identify an efficient method for printing 3D architectural models. The correct configuration of the main 3D printing settings, as well as the study of the influence on the structural characteristics, were performed in order to identify and solve the main faults of 3D FDM printing in PLA. The implementation of state-of-the-art resources, such as the quick response codes (QR codes), which provide interactivity to our model (virtual reality), enhanced the value of the walled enclosure of Priego de Córdoba.

5.2 Equipment and software

Different processes and technologies applied in our study, such as documentation techniques, three-dimensional modeling software, different 3D printing technologies and their

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[6] Gross printing time corresponds only to the material deposition process within the manufacture of a piece.

Table 1 Features of the filament used for 3D printing

Material	Colour	Diameter	Size	Nozzle Temp.
PLA	Ivory White	2,85 mm	M750g.	200–220ºC

corresponding equipment, as well as the latest generation interactive resources used were employed to achieve the final objective.

The geometric documentation technique was a complementary process to the study phase of the numerous archaeological actions carried out by the Municipal Historical Museum of Priego de Córdoba [21–24]. These studies have been depicted in other publications, as well as the various pieces of equipment used depending on the dimensions of the study object [35, 36]. The different documentation processes used complement each other perfectly under the same reference system and allow us to lay the foundations for the configuration of our three-dimensional model. Two 3D modeling programmes were utilized using different geometries. Meshlab 64bit_fp v2020.07 as the predominant software that uses a complex geometry configured through an organic model in the form of mesh, and 3DReshaper v.2018 (x64) under a temporary trial license. Blender v.2.82 was used to transform the aforementioned geometry in the form of mesh into a simplified and useful geometry to configure the three-dimensional model of the walled area.

These manufacturing technologies cannot be assessed without knowing the different materials. There are a wide variety of materials in which a three-dimensional model can be printed today [39]. Since the study was developed in the educational field, both, the FDM technique and the PLA fit the ecological purpose of respecting the environment [40]. Table 1 shows the features required to configure some printing parameters in our case.

Many printers use the technology described above for the manufacture of the pieces, which have different printing formats under the same Ultimaker Cura V.4.5 software. Three printers were chosen for this study according to the format. The Modix BIG-60 V3 3D printer (600×600×660 mm) was chosen for large format; Ultimaker S5 (330×240×300 mm) for medium format; and Ultimaker S2 Extended + (215×215×300 mm) for small format. Lastly, the multimedia resources for enhancing the value of the scale model were generated through the use of the latest-generation mobile devices and virtual reality through QR codes. To this end, Blender v.2.82 was used to render the 10 scenarios, krpano 1.20.10 to configure the 360º virtual tour and the web platform to generate free QR codes https://www.qrcode-monkey.com.

6 Results and discussion

The specific results are described below in depth for each phase after putting our method into practice.

6.1 Phase 1: Documentation

Much of the environment that the walled area occupies today was studied and documented before starting the creation of the virtual model. Numerous studies refer to historical, archaeological and currently existing data, using geometric documentation techniques. This documentation phase enables the creation of a sound virtual reconstruction.

Table 2 Precision allowed according to the scale determined by the visualization standard of the human eye (0.2 mm) and tolerance

Work scale	Highest precision (+ 1- mm)	Tolerance margin	Recommended precision (+ 1- mm)
1:5	1	2.5	2.5
1:10	2	2.5	5
1:20	4	1.5	6
1:50	10	1.5	15
1:100	20	1.5	30
1:200	40	1.5	60
1:500	100	1.5	150

6.2 Phase 2: Creation of the 3D model

The digital model is created using 3D modeling and subsequent texturing. This is the longest and most complex phase. For this, the geometric modeling developed from solid basic primitives and Boolean operations (union, subtraction and intersection) was used. In the cases where the result was a cloud of points and consequently an organic model constituted by a polygonal mesh, we simplified the result and transformed it into a more basic form.

6.3 Phase 3: 3D Printing process

At this point, 3 theoretical approaches to printing the model at the same scale (E 1:200) were analyzed. The same FDM technology was applied in all three cases, with a different 3D printer and different printing formats in each case.

6.3.1 Equipment and software

The choice of FDM technology with PLA[7] for the 3D printing of our model justifies the environmental educational purpose. As was previously mentioned, the project was developed with the collaboration and advice of the Department of Engineering Graphics, Design and Projects of the Higher Polytechnic School of the University of Jaén (Spain). It is worth highlighting the relationship between the development of interests and learning [41]. Polylactic acid, as a thermoplastic material, has a large number of properties: it is 100% biodegradable in aqueous media, at room temperature and in a pH range between 5 and 8 [40]. In addition, as relevant data, the production of 1 kg of PLA requires half the energy needed to produce a plastic of petrochemical origin, as long as its precursor is extracted from biomass [42].

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[7] Polylactic acid is a biodegradable thermoplastic of natural origin obtained from the fermentation of starch, cassava or sugar cane, which is characterized by being highly biodegradable. In addition, it has good mechanical properties, is strong and easy to handle when cooled, and hardens very quickly.

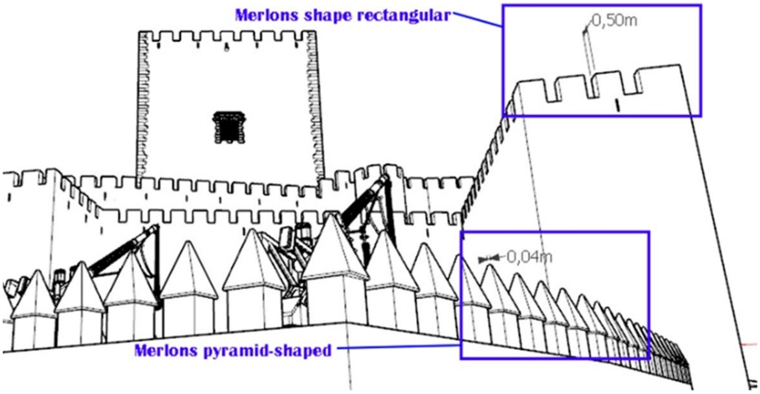

Fig. 2 Identification of the straight and pyramidal merlons to make up the scale model

6.3.2 Determination of the manufacturing scale based on the geometric characteristics of the model

The admitted precision depending on the scale is determined by the visualization standard of the human eye, 0.2 mm [43], and the tolerance margin defined for each specific scale. The scale to be represented is therefore calculated knowing the minimum size of the object to be represented or the maximum admissible error and the limit of visual perception. Thus, the minimum size or the maximum error to be represented has a minimum dimension of 0.2 mm for the most unfavorable case in the representation of the model. In the case of the scales of geometric documentation of heritage entities, the criteria used are based on the Technical Recommendations for the geometric documentation of heritage entities provided by the Andalusian Institute of Historical Heritage (Table 2), belonging to the Department of Culture of the Junta de Andalucía[8].

Some dimensions are verified after a geometric study of the 3D model to determine the printing scale. The most significant elements due to their small size and, therefore, those that will establish the 3D printing scale of the model, are the merlons. These are repeated numerous times throughout the three-dimensional model and their dimensions are the smallest. Comparing the 2 types of existing merlons (straight and pyramidal) at a geometric level, the pyramidal ones are the most decisive, since they have a geometry that makes their dimensions in the upper area minimal (Fig. 2), specifically 4 cm x 4 cm in real scale 1:1.

Taking as a reference the visualization standard of the human eye (0.2 mm.), the scale of 1:200 can be deduced as the one that enables the representation and appreciation of the element geometry, since an object that measures 4 cm will measure 0.2 mm at a scale of 1:200. Therefore, the chosen scale is the one that guarantees the correct representation of the smallest and most significant elements that make up the scale model. In this case, the

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[8] Technical recommendations for the geometric documentation of heritage entities provided by the Andalusian Institute of Historical Heritage, Ministry of Culture (Version 1.0 11/23/2011). https://www.iaph.es/export/sites/default/galerias/patrimonio-cultural/documentos/gestion-informacion/recomendaciones_tecnicas_documentacipm_geometrica..pdf (accessed 17 January 2024).

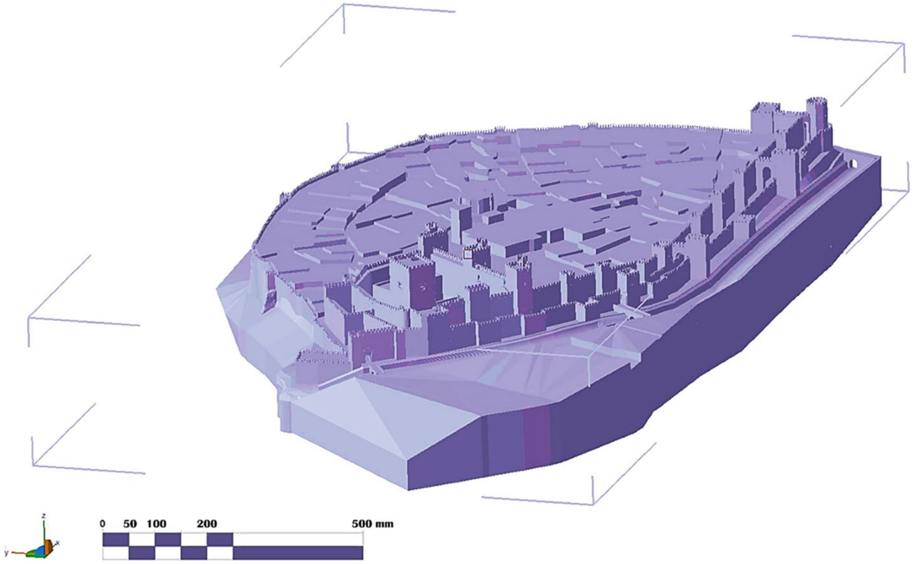

Fig. 3 1:200 scale representation of the model

chosen scale was 1:200. Therefore, the maximum dimensions of the model that are determined by the scale are: 1951.82 mm x 1111.64 mm x 286.89 mm. (Fig. 3).

6.3.3 Estimation of material savings based on the terrain topography of the scale model (calculation of the average slope of the longitudinal and transversal sections)

The estimation of material savings is determined by the characteristics of the orography of the terrain of the model (calculation of the average slope of the longitudinal and transversal section). The data obtained are directly related to the hidden volume that can be replaced by a structural element (pillar) and do not affect the full representation of the model.

The terrain orographic characteristics are determined by the existence of a natural pit, with an average height of more than 20 m both on the "North" face and on the "East" face of the 3D model. The natural pit is developed along the 200 linear meters that the walled enclosure covers in the most unfavorable case. Therefore, the data obtained after calculating the average slope were 9.8% for the longitudinal slope and 12.43% for the transversal slope. Once the most unfavorable slope was determined, a considerable hidden volume was deducted, which can be replaced with efficient pillars that allow saving volume and, consequently, material.

Three types of orography assignable to the model were proposed, depending on the maximum slope and on the 3D printing format:

1. Flat orography (estimated most unfavorable slope between 1% and 5%): the use of a large-format 3D printer is proposed, since it is not possible to save material.
2. Moderate orography (estimated most unfavorable slope between 5% and 15%): the use of a medium-format 3D printer is proposed to have an efficient printing and the consequent saving of material.

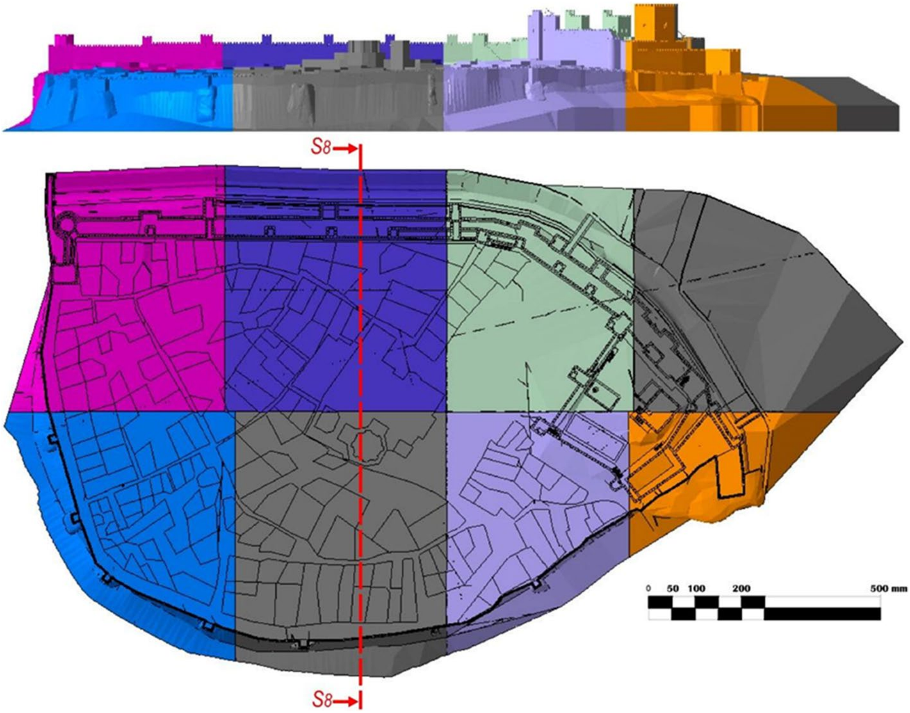

Fig. 4 Pieces distribution with Modix BIG-60 V3 (Maximum Printing V. 600×600×660 mm). Result: 8 pieces

3. Strong orography (estimated most unfavorable slope greater than 15%): the use of a small-format 3D printer is proposed, which produces the greatest material saving.

A medium or small format printer was chosen to save the maximum volume of material, since the maximum slope in the case study was 12.43%. The most unfavorable slope is determined by the large hidden areas that originate in any architectural scale model where a high slope of the land is represented. Models with flat orography do not have hidden areas; therefore, it is not possible to save a large amount of material. In this specific case, for a slope of 12.43%, the smallest-format printer was chosen, resulting in 100 pieces and a material saving of 31%.

6.3.4 Choice of equipment for 3D printing (number of pieces that make up the model and configuration of parameters)

The proposed method requires an appropriate study of the 3D printers to be used. Three printers with different printing formats were selected, which offer several results in number of pieces, time and filament consumption:

- Large-format 3D Printer: Modix BIG-60 V3.
- Medium-format 3D Printer: Ultimaker S5.
- Small-format 3D Printer: Ultimaker S2 Extended Plus.

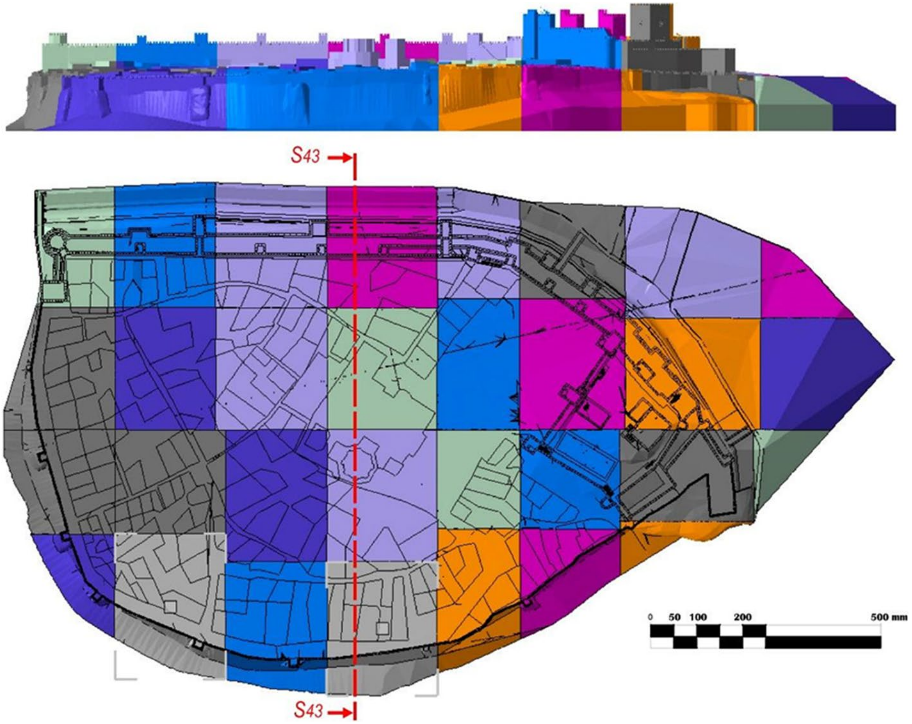

Fig. 5 Pieces distribution with Ultimaker S5 (Maximum Printing V. 330 × 240 × 300 mm). Result: 43 pieces

It should be noted that the larger the format of the 3D printing equipment, the smaller the number of pieces that will make up the final model. All the resulting pieces, as a common feature, have an associated file with an extension (*.stl)[9]. The pieces can be grouped into exterior or interior depending on their position. The former do not admit any simplification (there are no hidden areas along the height of the piece). On the other hand, those that occupy interior positions do admit material savings. The results generated by each equipment set are shown below (Figs. 4, 5 and 6).

In view of the results obtained in the theoretical study, it was decided to carry out the physical 3D printing using the Ultimaker S2 Ext. equipment (100 pieces), which presents a greater saving of material and net printing time. Therefore, it is the most efficient print for our case.

In order to determine the configuration of the 3D printing equipment, there are several parameters to take into account, which are determined by both the material and the printing equipment used [44]. Based on the experience and trajectory of the Department of Engineering Graphics, Design and Projects, which acted as an advisor during the 3D printing process of the project, the following parameters were entered in the configuration mode customized from the Ultimaker Cura V.4.5 software (Fig. 7).

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[9] STL (STereoLithography) is a CAD (computer-aided design) file format that defines the geometry of 3D objects.

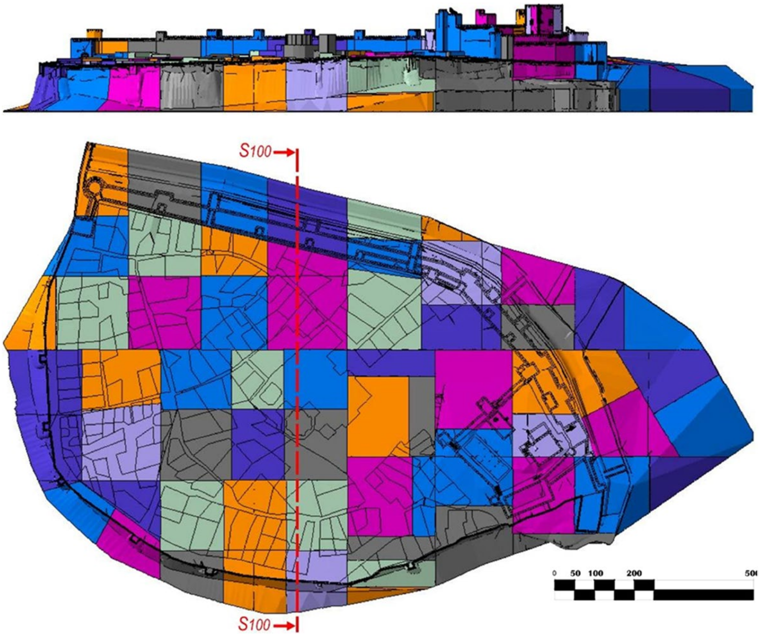


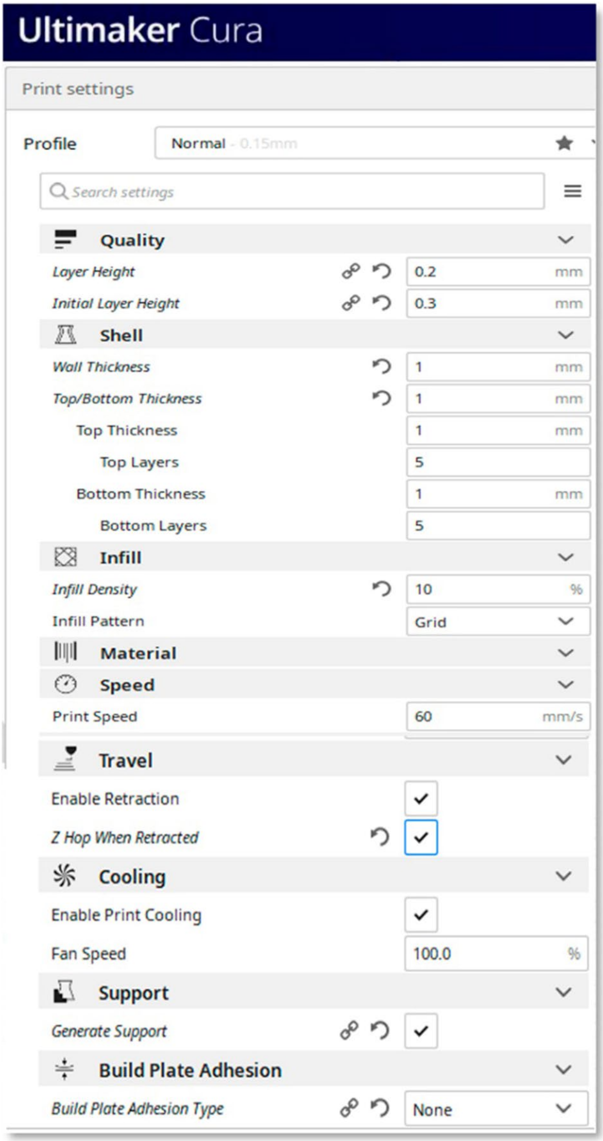
Fig. 6 Pieces distribution with Ultimaker S2 Extended Plus (Maximum print size 215×215×300 mm). Result: 100 pieces

1. Quality: the surface quality of the piece is determined by the Layer Height parameter and depends directly on the diameter of the extruder nozzle. It is recommended to print with layer heights of approximately 50% of the extrusion diameter of the equipment [45]. In this case a 0.4 mm extruder was used, thus the layer height parameter was 0.2 mm. This parameter does not affect the amount of material used, but it does affect the printing time.
2. The second parameter refers to the Line Width or extrusion diameter, in this case 0.4 mm.
3. The third and last parameter relative to the quality, the Initial Layer Height, affects the adhesion of the first layer to the printing platform. Therefore, it is recommended to be somewhat larger, specifically 75% of the extrusion diameter [45]. A layer height of 0.3 mm was used in this case.

Shell/Perimeter upper, lower and exterior walls. The Wall Thickness must always be a multiple of the diameter of the extrusion nozzle. Prints are recommended to have a wall thickness of 2–4 mm. This is equivalent to a total thickness of 0.8–1.6 mm, with 1.2 mm being recommended. Regarding the Top/Bottom Thickness, 1 mm is recommended, both for the upper and lower areas. It is not recommended to be smaller, since this could affect the aesthetic result [45].

Infill this is the grid that defines the internal structure of the piece. This setting decides the density of plastic filling the model inside of its perimeter, bottom and top layers [46, 47].

Fig. 7 Printing setup with Ultimaker Cura V 4.5



Ultimaker Cura

Print settings

Profile: Normal - 0.15mm

Search settings

Quality

- Layer Height: 0.2 mm
- Initial Layer Height: 0.3 mm

Shell

- Wall Thickness: 1 mm
- Top/Bottom Thickness: 1 mm
  - Top Thickness: 1 mm
    - Top Layers: 5
  - Bottom Thickness: 1 mm
    - Bottom Layers: 5

Infill

- Infill Density: 10 %
- Infill Pattern: Grid

Material

Speed

- Print Speed: 60 mm/s

Travel

- Enable Retraction: ☑
- Z Hop When Retracted: ☑

Cooling

- Enable Print Cooling: ☑
- Fan Speed: 100.0 %

Support

- Generate Support: ☑

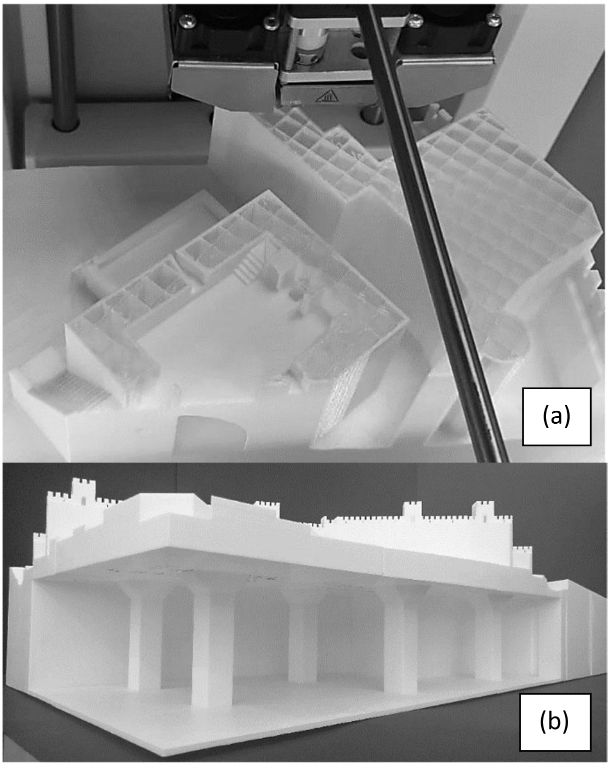
Build Plate Adhesion

- Build Plate Adhesion Type: None

The shape and density of this parameter affects the resistance, the printing time and the amount of material used. For pieces that are not subjected to great stress, the infill can be 15%. If they are part of a mechanism, it should be 20–40%, and if maximum resistance is to be achieved, the infill, must be 100%. In our case, the pieces were not subjected to any stress; therefore, a minimum filling value of 10% was used (Fig. 8a).

Material there are several configurable parameters in this block, such as the ’printing temperature’ that the extruder must reach to melt the material, which, in any case, is supplied

Fig. 8 3D printing process: **a** 'keep'; **b** Hidden area inside a part of the model



when purchasing the material. Our filament melts at 200-220°C, although other authors indicate 190°-300° [46].

Build plate temperature this feature, which not all printers have (despite being recommended), has a range of 50-60°C. Its suitable value is 60°C. The activation of '***Enable retraction'*** is recommended, since it improves the quality of the prints and reduces the generation of threads in the pieces.

Speed this parameter is related to print quality and printing time. The higher the speed, the shorter the printing time and the worse the print quality. The first parameter, sprint speed, refers to the speed at which the extruder should move while it is laying the molten filament. To obtain an optimal result, whose interval is 50–100 mm/s, 60 mm/s was chosen, guaranteeing a good print quality and a not-very-short printing time [46]. The second parameter, '***Travel speed'***, is the speed of the extruder when it is not laying material. In this case, the maximum value of the mentioned interval, 100 mm/s, was used.

Travel the parameters to configure are "Retract before outer" Wall" and Z hop When retracted". They refer to the extruder retracting before the outer layer starts in the first case and upwards when it moves from side to side in the second case. In both cases, its activation is recommended to avoid collisions with the piece.

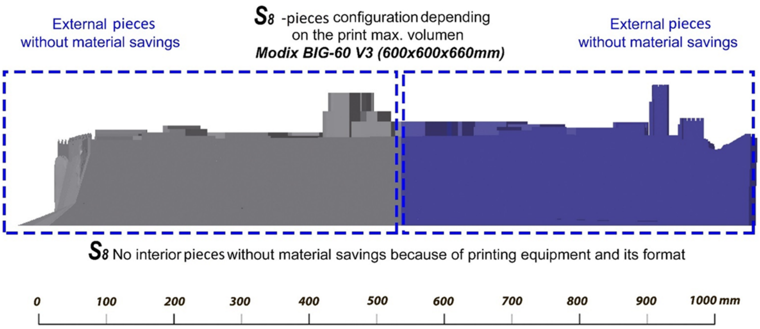


Fig. 9 S8 Transversal section and pieces configuration for Modix BIG-60 V3 (600×600×660 mm.) Total 8 pieces

Cooling this parameter activates the heater block cooling fan (100% recommended), and thus prevents excessive temperatures, which may oxidize the material and produce errors and quality defects in the pieces.

Support the use of this resource depends on the morphology of the piece to be printed; in this case, the pieces of this model are structurally load-bearing (vaults, arches, stairs, cuts, walls, etc.). No auxiliary structures were needed to support overhangs in our pieces. It was possible to segregate the model, leaving the pieces with an adequate orientation, good support and thus a well-configured printing base. However, it is worth highlighting the efficient pillars designed to support the interior pieces and whose hidden volume was eliminated to save material (Fig. 8b). A cantilevered capital with an angle of 45° was designed in these elements. The range for printing with PLA is 40°-60°. Therefore, our design allows us not to use supports (Support Overhang Angle).

Build plate adhesion this parameter allows creating structures on the printing plate that improve the adhesion of the piece to the base and prevent it from coming off. In this case, we did not only dispense with this resource, but lacquer was also applied to the base to facilitate the detachment of the piece once the printing process was complete.

The configuration parameters for the 3D printing were the same for each of the 3 printers used for our theoretical assumption. The time estimate generated by the Ultimaker Cura 4.5 3D printing software was fulfilled almost perfectly, obtaining a variation 2–5% with respect to real time. It is worth mentioning the robustness of the printing machine, as well as its extruder (it did not require any replacement throughout the 165,600 min of work that it was used in printing the 100 pieces of the model). The errors found during the printing process were minimal and consisted in the generation of excess filament threads in some pieces. These were caused by not having enabled retraction on some occasions. This absence of errors was caused due to the maintenance operations carried out before printing each piece or each time the material or filament was replaced. This process consisted in purging the material remains, preventing them from being solidified inside the nozzle. Using a metal rod with a diameter smaller than that of the filament, and once the extruder was heated to a temperature slightly higher than the melting temperature of the material, it

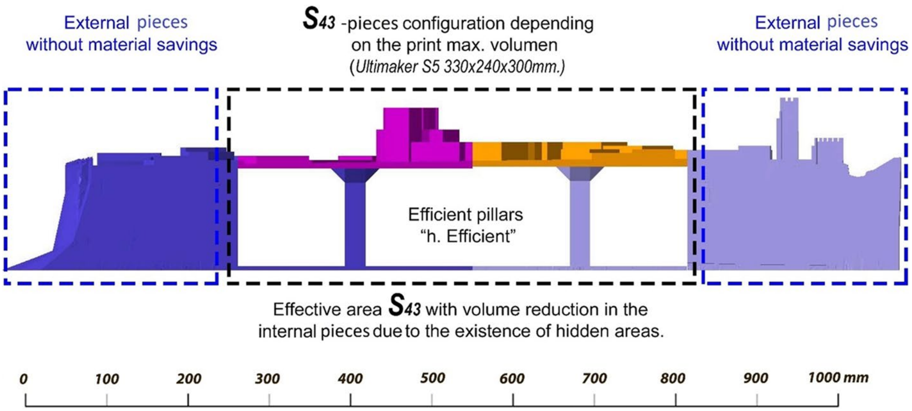


Fig. 10 S43 Transversal section and pieces configuration for Ultimaker S5 (330 × 240 × 300 mm.) Total 43 pieces

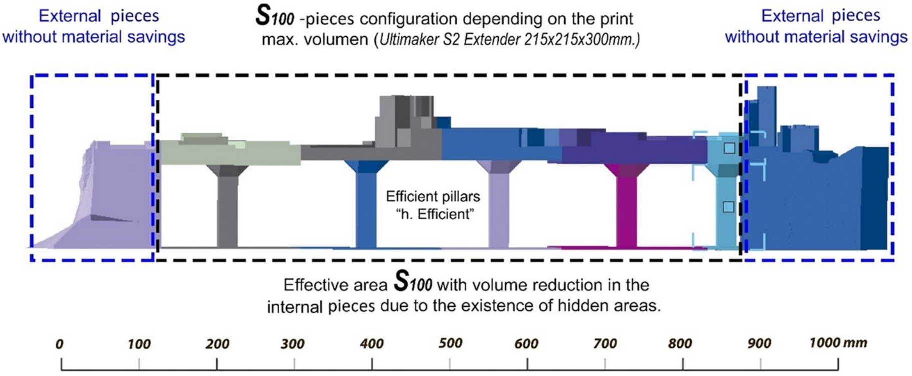


Fig. 11 S100 Transversal section and pieces configuration for Ultimaker S2 Ext. (215 × 215 × 300 mm). Total: 100 pieces

was carefully pushed with the metal rod and, later, with the "move material" option, inside the equipment maintenance function, any residue was expelled.

6.3.5 Delimitation of the model areas: exteriors (pieces without material savings) and interiors (pieces with material savings)

The 3D printer Modix BIG-60 V3 is conditioned by its large printing format (600 × 600 × 660 mm), which allows the entire model to be made in 8 pieces (Fig. 4) and does not give rise to internal areas. Consequently, there is no volume reduction or material savings (Fig. 9). This case would correspond to a practical and non-efficient 3D printing. In the two remaining cases, the Ultimaker S5 equipment (Print format 330 × 240 × 300), made in 43 pieces (Fig. 5), as well as the Ultimaker S2 Extended Plus equipment (Print format 215 × 215 × 300), made in 100 pieces (Fig. 6), have internal pieces, with the possibility of volume reduction and material savings. This fact originates the design of some new elements, such as pillars with efficient height, which occupy the suppressed areas and support

Table 3 Results in number of pieces and printing time for the three printers under study

3D printer	Number of pieces	Time (min.)	%
Modix BIG V3	8	193,409	100
Ultimaker S5	42	180,129	93
Ultimaker S2E	100	165,600	86

Table 4 Results in number of pieces, filament weight (gr.) and volume

3D printer	Filament weight (gr.)	%	Volume (cm3)	%
Modix BIG V3	32,240	100	204,023	100
Ultimaker S5	24,510	76	125,195	61
Ultimaker S2E	22,102	69	96,500	47

the internal sectioned pieces, finishing with a minimum thickness (Figs. 10 and 11). All the interior pieces are given to apply the aforementioned concept, since they have areas that can be hidden and consequently provide a significant reduction in volume, material expense and net printing time.

Therefore, with both sets of equipment, an efficient print was achieved. Observing Figs. 10 and 11, which show both the outer pieces (without volume reduction) and the inner pieces (with volume reduction), the concept that a 3D printing of a model can be efficient and achieve considerable material savings is better understood. This fact is based on finding, firstly, the appropriate printing scale and, secondly, the 3D printer that allows for efficient 3D printing.

6.3.6 Determination of volume reduction depending on the type of 3D printer used and consequent % material savings

A file (*.gcode)[10] was associated with each of the resulting pieces using the Ultimaker Cura V4.5 3D printing software. The aim was to analyze, as a theoretical assumption, the results in net time, volume and filament cost of the same architectural model (E 1:200) for each of the selected sets of printing equipment. To this end, the same FDM technology was applied in all three cases, with a different 3D printer and a different number of pieces.

Tables 3 and 4 show the results. It is observed that the reference 3D printer Modix BIG V3 (600 × 600 × 660 mm.) is the most unfavorable of the three sets of equipment, since, due to its printing format, only 8 pieces would be needed (all exterior and none in the inner zone), thus there would be no material saving according to our proposed method. As expected, the net printing time, as well as its material consumption, was the highest. It specified 100% in net time, 100% in material and consequently 100% in printed volume. At this point, it is worth considering what percentage of savings can be achieved efficiently by applying the method. Table 3 shows the results of the printing

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[10] The G-Code language defines, by means of coordinates, the trajectory that the nozzle must follow, its speed, the temperature at which the plastic must be dosed, etc.

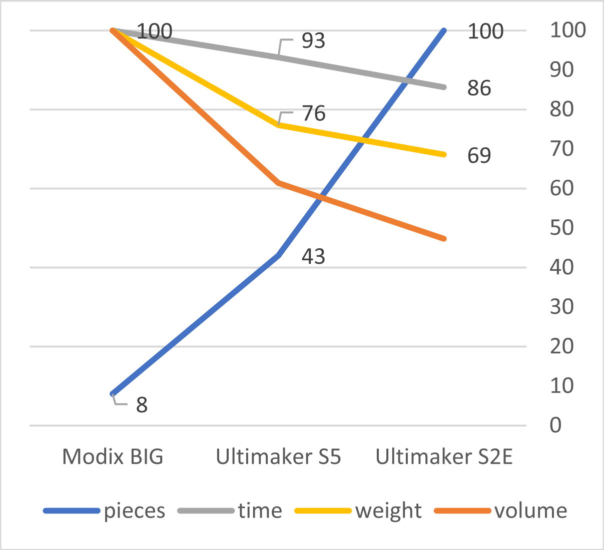


Fig. 12 Savings in percentage of time, weight of material (gr.) and volume with respect to the most unfavorable case Modix BIG V3 large format

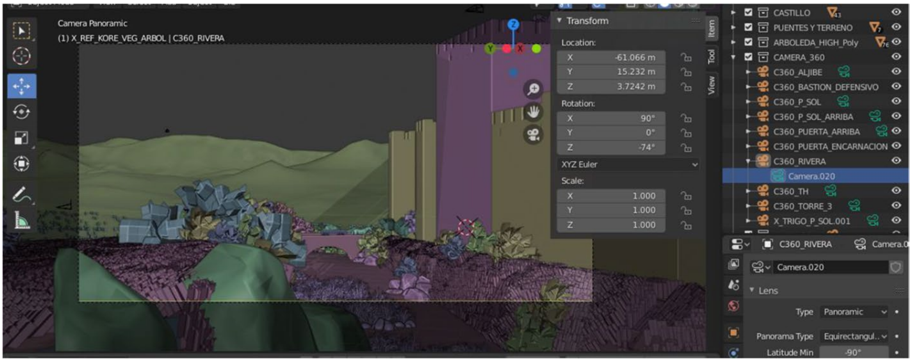
time and the amount of filament used to make each of the models. The smaller the printing format of the machine, the greater the number of pieces needed to complete the model. By applying the efficient method, greater material savings and shorter net 3D printing time are obtained, thanks to the partial removal of the volume.

Figure 12 shows the behavior of the percentage of savings in net printing time and, consequently, in material savings in the same proportion.

For an Ultimaker S5 medium format 3D printer (43 pieces), there is a decrease of 76% and 61% in filament consumption and volume, respectively, which implies a material saving of 24%. In the case of the Ultimaker S2 Ext (100 pieces), there is a decrease of 69% and 47% in filament consumption and volume, respectively, which implies a material saving of 31%. All percentages refer to the Modix BIG V3 3D printer, the most practical in total printing time, but the least efficient. This is due to the fact that the volume of material corresponding to the outer ring, which consists of the pieces that do not save material, is lower in the small-format 3D printer. The smaller the printing format, the greater the material savings and, consequently, the more efficient the printing. Net printing time is always considered over gross time. The latter would be the result of the sum of the net printing plus the downtime between changing objects, or while cleaning the printer, among others.

6.3.7 Finishes and final presentation of the scale model

The final printing result of the 3D scale model presented a total count of 100 pieces and the following dimensions: 1951.82 mm x 1111.64 mm x 286.89 mm (Fig. 3). Another important challenge arose: to carry out its assembly. Setting up 5 big blocks equally was the optimal way to achieve this. To this end, each block was created using a gluing system. There is a wide range of adhesives; in this case, welding adhesive for hard and rigid plastics was chosen. Another resource used for the areas that presented a worse fit was a bi-component putty for filling gaps.



Transform

Location:
X -61.066 m
Y 15.232 m
Z 3.7242 m

Rotation:
X 90°
Y 0°
Z -74°

XYZ Euler

Scale:
X 1.000
Y 1.000
Z 1.000

Type Panoramic
Panorama Type Equirectangul..
Latitude Min -90°

Fig. 13 Screenshot of Blender v.2.82, obtaining the 360º panoramic that provided one of the 10 scenarios of the 3D model

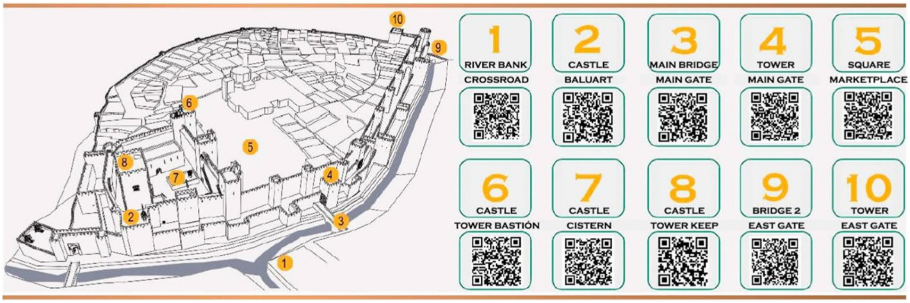


Fig. 14 Information panel located next to the model that shows interactive points with QR codes. https://turismodepriego.com/vr/

In relation to the finish, firstly a homogeneous base paint with single-layer acrylic spray enamel was used. Next, satin water paint of different colors was applied using the Faux finish technique and a wax aging process.

6.4 Phase 4: value enhancement of the model through a virtual tour through QR codes

This scale model was provided with the latest generation interactive resources. Several strategic points were selected within the three-dimensional model and different Blender v.2.82 options were configured to render the 10 scenarios that configure the virtual tour (Fig. 13).

Once the different 360º panoramic views were obtained, the krpano 1.20.10 software was used to configure the virtual tour using XML codes, and a tour of the 10 most significant scenarios was undertaken. This programming code provides the interactivity to the object. The interactive content must be uploaded to a private server. In our case, it was uploaded to the server of the Tourism Area of the City Council of Priego de Córdoba. https://turismodepriego.com/vr/.

As a last step to enjoying the virtual visit, it is necessary to have a next-generation mobile device with which to scan the QR codes. Figure 14 shows the information panel

Fig. 15 Final result of the interactive model at a scale of 1:200. Medieval walled enclosure of Priego de Córdoba, 15th century

with QR codes that accompanies the interactive model obtained. The result of the interactive model is presented in the Town Hall of the Priego de Córdoba City Council, where it was installed (Fig. 15).

The result consisted not only in adding value through the 3D printing technique, but also providing this model with a module to store information in a data array, such as a QR code. Therefore, the provision of educational and interactive resources that make the visit even more interesting and that have stimulated municipal interest in this type of technique is justified.

7 Limitations

As constraints to the inherent process of 3D printing, the need to overcome the limitation of this technology was identified, particularly in the context of mas-producing many pieces. Next, we highlight the considerations that mitigated some limitations addressed in our experience:

1. Print quality: producing large batches of pieces poses the challenge of maintaining consistency in print quality. Therefore, the same material, speed and printing temperature was used to avoid minimal deviations in the materials.
2. Avoiding the use of supports and reducing material waste. The presence of support structures during the 3D printing process contributes to material loss and affects the surface quality of the pieces. Therefore, we selected an approach that prevents the need for post-print manipulation in a large number of pieces, thereby minimizing the associated logistics and reducing material waste.
3. Differences in adhesion between layers: a uniform printing configuration was implemented to ensure consistent mechanical properties, which guarantees the mechanical stability of the manufactured parts and thus prevents variations in adhesion between layers.
4. Reliability in the choice of equipment: the choice of Ultimaker 2 Extended + printer was based on its high precision (reaching up to 20 microns), in order to minimize dimensional deviations in the pieces and ensure the reliable reproduction of the design.

These approaches lead to optimal results in 3D printing instead of obtaining a mere voluminous mass.

8 Conclusions

A new workflow was configured developing the process of obtaining the physical model with 3D printing technology in an efficient manner. A significant saving of material was obtained for the same result after the study of various cases (31%). Our theoretical assumption showed that the saving of material is determined by the slopes (longitudinal and transversal) represented by the orography of the terrain of the model. This process was time-consuming but effective and allowed developing concepts such as height and efficient pillars, both caused by the volume of material saved. Other concepts addressed are net and gross printing time. The difference between these two concepts is determined by the time dedicated to other tasks carried out after the printing of one piece and the start of the next one (equipment maintenance, downtime and time related to piece change). In this context, if we only consider the gross time when printing a larger number of pieces, the time used will be greater. However, as was previously mentioned, this fact may seem inconvenient if we do not consider saving material as a priority objective.

This study allowed us not only to understand each of the components that make up a 3D printer, but also to optimize the configuration of the different parameters that make up the manufacturing process in a simple way. The most common errors presented were identified to subsequently correct them. In relation to the previous question, it is worth highlighting the importance of practicing good maintenance on the 3D printer extruder before each new print to avoid clogging. Although the structural resistance in the manufactured pieces was not a determining factor, it was appropriate to identify those parameters that condition it and apply these minimum values, to ensure that they comply with the minimum resistance standard for use and handling. Indeed, the infill and shell parameters were the factors that most influenced these features.

The versatility of the printed 3D digital model should also be highlighted. In addition, to obtaining a real physical object (scale-model), creating a three-dimensional scene allows us to provide the model with an interactive resource through a virtual tour available via Smartphone or virtual reality goggles.

This fact makes this project innovative and unprecedented in two areas that complement each other. In the field of tourism, this project establishes Priego de Córdoba as a pioneering city in the use of state-of-the-art resources and technologies, supporting and valuing the dissemination of its rich architectural heritage. In the didactic field, this work promotes the ecological concept and transmits constructive and architectural aspects of a time in our history characterized by the marked warlike nature of society. This study provides educational resources for the tourism sector and contributes to the dissemination of heritage resources in an understandable way.

Abbreviations ABS: Acrylonitrile Butadiene Styrene; CAD: Computer-Aided Design; FDM: Fused Deposition Modeling; PLA: Polylactic Acid; QR code: Quick Response; STL: STereoLithography; 3D: Three dimensional

Author contributions M-AR-P and D-FG-M contributed to the conceptualization; D-FG-M,RC-A and J-MM-G were involved in the methodology; RC-A, M-AR-P and D-FG-M contributed to the validation; D-FG-M, RC-A, J-MM-G and M-AR-P were involved in the investigation; M-AR-P contributed to the resources; D-FG-M contributed to the data curation; D-FG-M, RC-A contributed to the writing—original draft preparation; D-FG-M, RC-A and M-AR-P were involved in the writing—review and editing; D-FG-M, M-AR-P contributed to the supervision. All authors have read and agreed to the published version of the manuscript.

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Data availability The datasets and code generated during the current study are available from the corresponding author on reasonable request.

Declarations

Ethical standard Not applicable.

Conflict of interest The authors declare no conflict of interest.

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