Digitally Preserving Architecture: A Comparative Case Study of Leicester Cathedral and the Samcheong Hanok, With a 3D-Printed Hanok Model

Sophia Kou[1]

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This research studies the use of 3D printing and digital modeling as engineering tools for the preservation of architecture in both historical and modern contexts. It specifically considers the way in which 3D printing can be used to show historical buildings, thus enabling architects, historians, researchers, teachers, and the general public to learn about and value cultural history. The research attempts to find out what information about a historic building is still available after it has been altered, depending on whether or not it had been documented in 3D earlier on. In order to address this question, six types of information were compared in the published records of two buildings: Leicester Cathedral in England, which was laser scanned before its reordering, and the Samcheong Hanok, a privately owned house in Seoul built around 1940 and renovated in 2000. Furthermore, a published digital model of a hanok was measured against the roof proportions that Shin (2024) obtained from 61 Korean temple buildings and was then 3D printed using polylactic acid (PLA) in order to demonstrate how a digital model can be checked and transformed into a physical teaching aid. The comparison revealed that only the records of the scanned cathedral preserved the accurate 3D geometry and the hidden spaces, while both buildings retained their images and floor plans. For these two buildings, this suggests that only a 3D survey made before an alteration preserves a building's exact geometry, whereas drawings and photographs preserve its layout.

Keywords: architectural preservation, 3D printing, hanok, roof proportions, cultural conservation, heritage documentation

Introduction

Old buildings are more than just beautiful objects; they contain information about the way people lived, the beliefs they had, and the types of buildings they knew how to build, so that one roof or wall can at the same time show a culture's artistic achievements and its engineering skills. However, in today's rapidly changing cities many historic buildings are destroyed by natural disasters, through neglect, as a result of war, or because of urban development. Even though new technologies such as three-dimensional (3D) scanning, digital modeling, and 3D printing offer ways of recording them, a record is of no use unless the people who need it are able to find it, understand it, and make use of it.

For example, from the 1960s as South Korea became more urbanized and modernized, Western-style houses and apartment blocks replaced a large number of traditional hanoks, which are wooden Korean houses with curved roofs and a focus on harmony with nature[1]. This kind of loss shows the importance of documenting historic buildings before they are altered or destroyed. One response is to develop methods for digital recording; for instance, in England the national heritage organization, Historic England, provides guidance on the digital recording of historic buildings by means of 3D laser scanning[2].

The article examines how 3D printing and various other methods, such as computer-aided design (CAD) modeling and digital scanning, can help individuals in documenting, researching and teaching cultural sites. By viewing preservation from the standpoint of design and information—that is, by considering the type of information contained in the record, how it is stored and who can make use of it—the project involves measuring the roof proportions of a digital model of a hanok and then 3D printing the model with polylactic acid (PLA). The study asks what kinds of information about a historic building are still available after it has been altered, depending on whether or not it had been previously documented in 3D. It is hypothesized that a building which had been scanned in 3D before a major alteration retains more kinds of information—especially accurate 3D geometry and hidden structure—than one that had been recorded only by

[1] *Henry M. Gunn High School, USA*

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means of drawings and photographs, while basic appearance and floor plans are retained in both cases.

The study has two objectives: first, to compare the information in the records of two particular buildings, and second, to show, by means of a hanok model, how a digital model can be checked against the published roof proportions and then turned into a physical object that people can hold and examine. The hanok model is to be regarded as a demonstration and not as a reconstruction of a real building, and the study does not attempt any structural or thermal analysis. Because it focuses on only two buildings, one in each country, the conclusions reached in the study pertain only to these two buildings.

Why Architectural Preservation Matters

By keeping buildings as they are, we preserve the knowledge contained in the methods of construction, the materials used, and the overall designs. Historic buildings illustrate the way engineering has evolved over the years—from stone arches and wooden frames to domes which distribute the weight—and show how builders have turned this engineering into attractive shapes. In England, legislation for preservation and government financing have enabled a detailed study of many such buildings and have allowed them to be opened to the public.

South Korea has also kept a detailed record of its important heritage. Since the 1960s the national heritage agency (now the Korea Heritage Service) has prepared inventories and produced measured drawings of cultural properties; it has been running a national 3D laser-scanning database project since 2011 and makes its digital inventory data available to the public through the Korea National Heritage Online service [3]; moreover, it publishes measured 3D models of heritage buildings as open data on the country's Public Data Portal, for example a 3D model of the Buyongjeong Pavilion at Changdeokgung Palace [4]. Guidelines for the 3D scanning of cultural heritage were prepared in 2012 and finalized in 2015 [5], and the laser scan data obtained before the 2008 fire at Sungnyemun Gate have been used in the restoration work [3,6]. Korean researchers have developed building information models (BIM) of historic timber buildings, which are referred to as heritage BIM (HBIM) [7,8], constructed a scan-to-BIM archive of the Hwanggungwoo in Seoul [9], and carried out a digital reconstruction of Suwon Hwaseong [10], and Seoul hosted the 2025 international symposium of CIPA Heritage Documentation on the topic of moving from digital documentation to data-driven heritage conservation [11].

The problem lies rather in houses which are privately owned and not protected. Even in areas such as Bukchon, where traditional hanoks can still be seen, many have been renovated without first being digitally recorded, and the renovation process itself can reorganize the traditional spaces of a hanok [12]. As a result, details such as how the weight was supported, how the various parts were joined, and what materials were used may not be recorded, which makes it difficult to produce a model, carry out repairs, or rebuild them accurately in the future.

3D printing and digital modeling might help to fill this gap. They are able to produce detailed records of architectural structures and make small-scale replicas [13,14], thus allowing preserved buildings to serve as gateways to history and as tools for learning in the areas of design, materials science, and civil engineering.

Digital Documentation Tools

The rapid advancement of digital tools has changed the way people think about the preservation of architecture. Techniques including 3D laser scanning, CAD modeling and 3D printing (which is also referred to as additive manufacturing) offer non-invasive ways of recording and restoring historic buildings [2]. They simplify the accurate recording and reconstruction of buildings as well as providing access to education, engineering research and cultural appreciation.

The two main ways of recording the three-dimensional shape of heritage sites are laser scanning and photogrammetry [13]. A terrestrial laser scanner records millions of points in the form of a "point cloud," which can then be used to produce building models and virtual reality (VR) environments, as well as for educational use [15]; photogrammetry generates 3D models from a sequence of overlapping photographs, the quality of the resulting model depending on the software used [16]; and the light detection and ranging (LiDAR) sensors present in some phones and tablets allow for quick surveys of objects that have simple shapes, although with lower accuracy [17,18]. It is possible to gain advantages by combining these techniques: at the Magoksa Temple in Korea, ground-based scanning provided the most accurate position data while drone photogrammetry was used to capture the roofs [19]. Point clouds can be transformed into BIM or HBIM models [20,21], but the process of going from a scan to a BIM model is still largely manual and time-consuming [22–24], and HBIM is not yet effective at storing historical information [25]. The level of detail (LOD) and the level of information (LOI) show how much geometric and non-geometric information a model contains [26].

Digital records can also be shared and reused, which allows a larger number of people to make use of them. By using augmented reality (AR) and VR, individuals are able to explore heritage sites from a distance [27] and this can increase awareness of the value of such heritage [28]; digital twins can help with preventive conservation [29] and 3D printing can turn digital models into physical copies for use in research, education and museums [14,30–32], generally in a relatively short time and at a low cost [33]. As these visualizations combine evidence

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with interpretation, both the London Charter and the Seville Principles stipulate that the sources should be made clear[34,35]. Digital records have been especially useful after disasters, for example after the 2019 fire at Notre-Dame de Paris[36] and in the case of the destruction of the Temple of Bel in Palmyra, which was partly reconstructed in 3D from photographs taken by tourists[37].

Methods

Study Design

The study involves a qualitative comparison of two existing buildings together with the use of a design model. In order to carry out this comparison, the published records of each building were handled in the manner of an archive and examined for six types of information: exterior and interior appearance (in the form of photographs or images), floor plan, accurate 3D geometry, hidden structure and spaces, the history of changes, and the way in which the records were later used (see Table 1). The hypothesis is accepted if the kinds of information found only in the scanned building are accurate 3D geometry and hidden structure, and is rejected if the records of the Samcheong Hanok also include these features or if the cathedral's records fail to include them. The hanok model was used to show how a digital model can be checked and then turned into a physical teaching aid: the proportions of its roof were measured and compared with those given by Shin[38] (see Table 2), after which it was 3D printed. Since the model does not correspond to any specific building, there are no measured drawings or scans of an actual building available against which its geometry can be checked, and therefore no point-to-surface error can be calculated; the work is thus presented as a constructive review based on a design model rather than as a validation test.

Case Study Selection and Comparative Framework

The study concentrates on two case studies, namely the 3D scanning and modeling of Leicester Cathedral in England and the renovation of the Samcheong Hanok in Seoul. In each case there was a significant change and records of the work have been published, but only the cathedral was previously scanned in three dimensions. The two cases also differ in respect of ownership, statutory protection, funding, scale, building type and the purpose of the project; Leicester Cathedral is a Grade II* listed building[39] and the survey of its reordering was carried out by a commercial survey company which had been engaged by the architects[2], whereas the Samcheong Hanok is a privately owned house which an architect renovated for a client in 2000[1]. Because there is only one example in each country it cannot be determined whether the influence of national policy or that of the individual case was greater, and so the conclusions of the study apply only to these two buildings.

Case Study 1: Digital Documentation and Preservation of Leicester Cathedral, England



Figure. 1 Leicester Cathedral, which was laser scanned prior to its reordering. Photograph: "Leicester Cathedral 39 Exterior 01a Cathedral 3pan" by Peter from Lincoln, UK, from Wikimedia Commons (`https://commons.wikimedia.org/wiki/File:Leicester_Cathedral_exterior.jpg`), licensed under CC BY 2.0 (`https://creativecommons.org/licenses/by/2.0/`).

Leicester Cathedral was originally built in the Norman period and was then rebuilt over a number of centuries (see Figure 1); it was digitally scanned in order to aid both the reburial of King Richard III and a major redesign of the interior[2]. The surveying company Plowman Craven used a Leica P40 laser scanner capable of recording one million points each second and with a specified 3D positional accuracy of 3 mm at a distance of 50 m[40]; Historic England says that an accuracy of 3 mm was maintained throughout the survey[2]. It was therefore possible to obtain a complete and accurate spatial record of the building without needing to touch it[2].

The project shows that it is possible to offer accurate, scalable and non-invasive techniques for heritage conservation by using advanced scanning tools in conjunction with high-dynamic-range (HDR) imaging, parametric Revit modeling, and cloud-to-cloud registration through Leica Cyclone; the survey dealt with not only the visible architectural features but also the hidden parts of the building, since, in order to plan the siting of the new tomb, records were made of the thickness of the floor slabs and of a service tunnel beneath the main floor[2].

Since the cathedral was left open during the project, the survey team was obliged to scan certain areas at particular times so as not to disturb the daily routine. Moreover, in order to handle safety hazards such as confined spaces and exposure to asbestos they followed strict safety procedures and used protective equipment[2].

The interior details in the final Revit model were developed at LOD 2 and LOI 200 and the exterior details at LOD 3 and LOI 300 (the case study not stating which standard determines these levels) so that future design work could be carried out, and the point-cloud database has now turned into a complete archive record which can be accessed at any time[2]. This example illustrates the way in which tools such as 3D scanning and BIM are transforming the field of heritage preservation by offering safer and more accurate methods for documenting and protecting historical sites while maintaining their integrity and ensuring their adaptability for the future.

Case Study 2: Documentation and Renovation of the Samcheong Hanok, South Korea

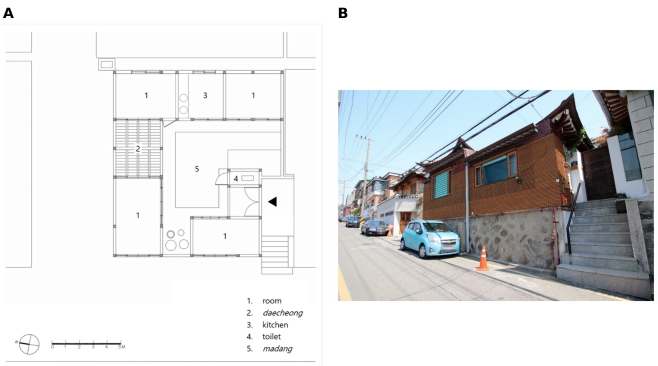


Figure. 2 The Samcheong Hanok before and after renovation. **A)** Plausible floor plan of the original urban-type hanok in Samcheong-dong, Seoul, when first built around 1940, as reconstructed by Lee and Kim. **B)** A renovated version of the same hanok, completed in 2000 by architect Wook Choi[1]. A and B are Figures 9 and 2 of this source (drawing and photograph by the source's author), reproduced under a Creative Commons Attribution license (CC BY 4.0, `https://creativecommons.org/licenses/by/4.0/`); in B, vehicle license plates have been blurred.

The Samcheong Hanok, located in Seoul's Bukchon Hanok Village, is a privately owned house. It was originally built about 1940 as an example of mass-produced urban-style hanok and was subsequently renovated in 2000 to convert it into a modern house. Although its external appearance still retains the traditional Korean design, the available sources do not contain a 3D metric survey or a structural model of the house. Nevertheless, drawings (including plans, sections and elevations) and photographs of the house before and after the renovation do exist[1] (Figure 2).

What is lacking, then, are a three-dimensional metric survey and a structural model, not all of the records: it was still possible for Lee and Kim to trace the various extensions and repairs to the house by referring to the existing drawings and photographs[1].

The example of the Samcheong Hanok shows that, as this house was renovated without performing digital preservation, its exact 3D shape and structure were not recorded, even though the building appears traditional from the outside.

Digital Modeling and Fabrication Workflow

The process of preserving architecture through the use of 3D modeling and printing involves a number of tools, beginning with the scanning equipment and concluding with the printer. For houses such as the Samcheong Hanok, whose original form was never surveyed in 3D, any 3D version of that form can only be a model, not a measured record, and such models need to be checked against measured data before they are used. The rest of this section describes the model and the steps that were carried out in this project to turn a digital file into a physical object.

A published model was used merely as a visual reference: "Hanok," uploaded by user heydotory to Sketchfab[41]. It shows a typical hanok with a hip-and-gable (paljak) roof, a front porch and a raised stone platform, along with its own tile, wood and stone texture representations. Since the model can only be viewed online and is not accompanied by any license, neither its geometry nor its textures were used, and no images of it are included in this paper. The model that was measured and printed is in fact a different, already published model: "A Traditional Korean House," which was shared on Thingiverse by user hyojung0320 under a Creative Commons Attribution (CC BY) license, which allows it to be printed, measured and displayed on the condition that credit is given[42]. This house has an H-shaped plan with a main hall located between two wings, each of which has a paljak roof; it includes twelve free-standing round columns on hexagonal foundation stones, thin solid walls, solid roofs with rows of tiles on their surface, and has no internal timber frame. The model does not represent a specific building, and all the dimensions of the model mentioned in this paper were taken from the model file; none of them were derived from a drawing or a photograph of an actual building.

The STL (stereolithography) file employed for the printing process is called a_traditional_Korean_house_printing.stl. As the designer has not given a real-world scale, the dimensions are given in millimeters as they appear in the model file and are compared to Shin's buildings solely on the basis of ratios and angles, neither of these comparisons depending on scale.

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So that it could be physically preserved and displayed, the model was prepared in UltiMaker Cura 5.9.0 and printed on a filament-based 3D printer (the Creality Ender-3 V2 Neo) with the use of PLA. It was reduced in size uniformly by a factor of 0.893 and printed upright on its base with a layer height of 0.2 mm, a 0.4 mm nozzle, 20% infill, and no supports. Cura calculated that the printing would take about 14 hours and would use around 78 g of PLA; the actual printing time on this printer was about 15 hours. The model file was made in Rhinoceros, and in this file the various parts overlap rather than forming a single closed, manifold mesh, Cura printing the overlapping parts as one volume by default. Tangible copies of this type can be used to aid education, documentation and preservation efforts.

Roof Geometry Parameters

Real digital preservation does not just involve reproducing the appearance of a building; it also requires understanding the design principles behind it. The hanok roof is an instance of the combination of art and engineering: Shin regards the roof as the most beautiful part of a hanok and has noted that its proportions have an effect on the building's appearance[38]. In his 2024 study in the journal *Buildings*, Shin looked into the geometric rules that apply to traditional hanok roofs by examining 61 temple buildings which have been designated as national heritage items[38].

The study found consistent design features, specifically that the ratio of eave height to roof height is on average about 55 to 45, even though the individual heights vary from building to building, and that the sum of the eave angle and the roof angle is between 118° and 120°. Shin measured the eave height from the top of the foundation stone, this being at the same level as the bottom of the column, and the roof height separately[38]; in the current paper, however, the eave height is measured to the end of the eaves and the roof height from the end of the eaves up to the bottom of the yongmaru, which were the points that Shin had used to determine the roof angle. The measured values from the finished model are listed next to Shin's in Table 2.

The two angles are defined in different ways and so should be different (Figure 3). The eave angle is taken at the bottom of the column, being the angle between the column and the line drawn to the end of the eaves. The roof angle is measured at the end of the eaves, being the angle between the line to the bottom of the yongmaru (that is, the ridge at the top of the roof) and the line to the bottom of the column; Shin's ranges for both angles are given in Table 2[38]. The eave overhang and the eave angle mainly serve a shading function, while the roof angle determines how much of the roof is visible from the front and is what gives the roof its appearance[38]. Because the total of the two angles changes very little, a smaller eave angle corresponds to a larger roof angle, and hence a roof should not be designed on the basis of the average of either angle alone[38]. The figure of 119° represents only the average of this sum and is not an angle that can be measured at a single point on the roof.

The types of buildings that Shin used were all the same: out of the 61, each one was a temple building included in the list of national heritage sites, and almost all of them had double eaves with long overhangs[38]. Since this is the case, Shin's diagram of the measurement points is based on a section of a temple hall equipped with bracket sets[38]. As Shin has not designated a separate category for houses, his ratio and angle total have not been proven to apply to a house; they are therefore used here only as reference values for comparison instead of serving as design rules, and the comparison also shows how much a small house model differs from them.

In order to be able to compare the printed model with the relevant values, three measurement points were chosen in a transverse section that passes through the middle of the main hall of the model file (Figure 3): the lowest point of the front columns at the highest part of their foundation stones, the point where the eaves end at the lowest part of the outermost edge of the roof, and the point at the bottom of the yongmaru where the ridge meets the two roof slopes. All the values were derived from the model's triangle mesh by means of a short Python script.

Under Shin's system—this being the classification used in the present paper—the rafters are termed yeonmok, the chunyeo is the rafter positioned at 45° at each corner of a hip-and-gable roof, the purlins are called dori, the jongdori being the one at the ridge, and the yongmaru is the ridge situated at the top of the roof, above the tiles[38].

Results

Comparative Analysis

Leicester Cathedral and the Samcheong Hanok serve as examples of how engineering methods can affect the handling of architectural heritage. In the case of Leicester Cathedral, the aim was practical: to plan the new tomb for Richard III and to reorganize the cathedral[2]. The survey team was able to produce a complete point-cloud archive and a parametric model of the cathedral by making use of techniques such as 3D laser scanning, BIM and point-cloud registration. This meant that the physical details of the building were preserved and that future design work as well as long-term storage became possible[2].

On the other hand, the renovation of the Samcheong Hanok shows how heritage can be modified without first being preserved through documentation. Even though the renovated building has kept a traditional appearance, its records lack the

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Table 1 The information retained in the records of the two buildings and the facts concerning each project. "Not reported" indicates that the sources fail to provide this information.

Item	Leicester Cathedral	Samcheong Hanok
Exterior and interior appearance	Yes: HDR panoramic photographs and scan data [2]	Yes: photographs before and after renovation [1]
Floor plan	Yes: in the point cloud and Revit model	Yes: the architect's plans before and after renovation; Figure 2A is a reconstructed plan of the original house [1]
Accurate 3D geometry	Yes: point-cloud archive; Revit model (interior LOD 2/LOI 200, exterior LOD 3/LOI 300)	Not reported
Hidden structure and spaces	Yes: floor slabs and a service tunnel surveyed	Partial: sections survive; no structural model reported
History of changes	Not reported in the case study	Yes: successive extensions and repairs traced
Later use of the records	Planning the tomb and reordering; long-term archive	Architectural history research
Survey accuracy	3 mm maintained throughout the survey [2]; scanner specification 3 mm at 50 m [40]	No survey reported; accuracy of the drawings unknown
Data volume	Not reported	Not reported
Cost	Not reported	Not reported
Labor hours	Not reported	Not reported
Legal status	Grade II* listed building, first listed in 1950 [39]	No heritage designation reported; renovated before Seoul's hanok registration system (2001) and support ordinance (2002) [1]
Ownership	Church: cathedral of the Diocese of Leicester [2]	Private owner [1]
Funding	Not reported	Private; not supported by the Seoul Hanok Support Ordinance [1]
Who did the work	Survey company commissioned by the architects [2]	Architect (Wook Choi) for a client [1]
Where the archive is kept	Point-cloud database delivered to the client as an archive record [2]	Architect's drawings and photographs, published in 2000 and 2021 [1]
Public access to the data	Not reported	Yes: drawings and photographs published, including in an open-access article [1]
Date of the work	2010s (second scanning phase in 2016) [2]	2000 [1]

accuracy and completeness which could have been obtained using engineering tools. Neither a 3D scan nor a structural model of the original house is mentioned, even though drawings and photographs of its earlier states do exist [1]; the layout and history of the house can still be studied, but its exact 3D geometry cannot be reconstructed (Table 1).

Table 1 shows that the only building for which both accurate 3D geometry and a record of hidden spaces such as the floor slabs and the service tunnel were preserved was the scanned cathedral; in contrast, both buildings had images and plans and the hanok's drawings and photographs also contained a detailed history of its changes. The hypothesis is therefore supported in relation to these two buildings: as had been predicted, accurate 3D geometry together with a record of hidden spaces was found only in the case of the scanned cathedral; however, the hanok's drawings and photographs included a history of the changes, whereas the cathedral's case study does not give such information. The entries in the project rows of Table 1 show how different the two cases are: the cathedral is a Grade II* listed church which was surveyed by a commercial company on behalf of its architects, while the hanok is a private house that was remodeled for a client without benefiting from Seoul's hanok ordinance, and in each instance the cost, data volume, or working hours of the documentation are not reported. Because the two buildings differ in respect of ownership, level of protection, funding, scale, type and date, the findings apply only to these two buildings.

Hanok Model

The hanok model shows how a digital model is measured and then turned into a physical object; Table 2 compares the roof proportions with Shin's values, Figure 3 presents an annotated section of the model, Table 3 lists its main dimensions, and Figure 4 displays the designer's rendering of the model to-

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gether with photographs of the PLA print taken from five directions.

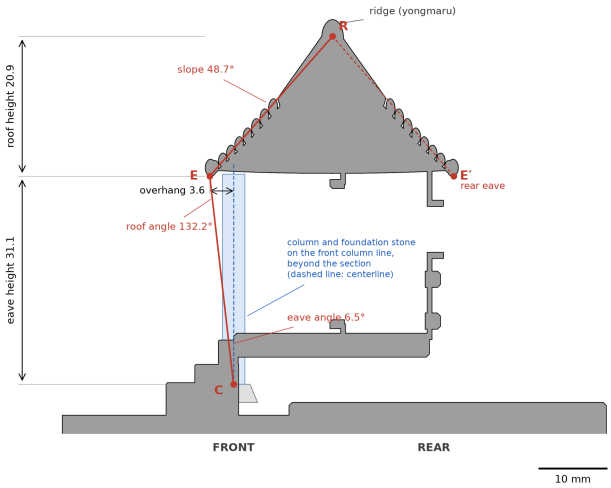


Figure. 3 A transverse section drawn from the model file of the printed model, passing through the middle of the main hall (the dimensions are given in millimeters and the front is on the left). The points referred to in Table 2 are C, the bottom of the column (that is, the top of the foundation stone); E, the end of the eaves; and R, the bottom of the yongmaru. E′ is the end of the rear eaves; the column and foundation stone on the front column line are located beyond the section and have been shown in projection. Model: "A Traditional Korean House" by hyojung0320[42], licensed under CC BY.

Table 2 and Figure 3 show a comparison between the printed model and Shin's values. The ratio of eave height to roof height in the model is higher than Shin's average, and the slope of the roof in the model is much steeper than Shin's. The eaves of the model extend only slightly beyond the front columns. As a result, the eave angle in the model is considerably lower than Shin's range and the roof angle is much higher than his, the sum of these two angles also exceeding Shin's range. The ridge of the main hall does not rise toward its ends; rather, it dips slightly between the middle and each end; Shin does not provide any value for comparison. These differences are consistent with the different kinds of buildings: the model is a small, stylized house, while Shin's sample consists of temple buildings, most of which have double eaves and much longer overhangs[38].

The model file is available on its Thingiverse page[42].

Discussion

In the case of the two buildings in question, 3D scanning had mainly provided accurate geometry and a record of the hidden spaces, whereas traditional drawings and photographs had still

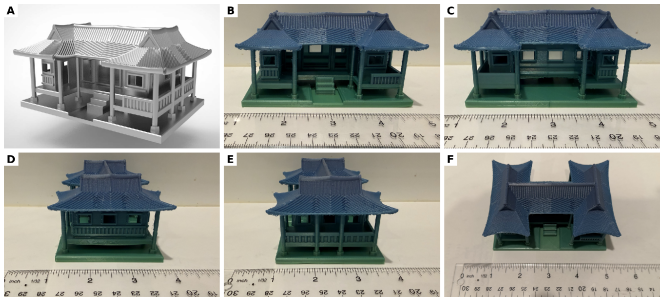


Figure. 4 The hanok model in the form of a digital file and as a physical print. **A)** A rendering of the model file created by its designer, hyojung0320[42] ("A Traditional Korean House," on Thingiverse), licensed under CC BY. **B–F)** The 3D-printed model (made from PLA and about 11 cm long), displayed with a ruler from the front (B), from the back (C), from the left (D), from the right (E) and from above (F), where the H-shaped plan is visible. Photographs by the author.

retained the Samcheong Hanok's layout and history. The difference seems to have more to do with the buildings' ownership and protection than with national culture; in South Korea as well, national heritage sites are scanned, and the laser scan data obtained before the 2008 fire at Sungnyemun Gate were used in the restoration of that site[3,6]. The gap therefore appears to lie in privately owned and unprotected houses rather than in national policy, although it should be noted that two examples do not prove this.

The hanok model shows the possibility of comparing a digital model with recognized proportions and of 3D printing it as a teaching aid. As the roof of the hanok model was steeper and its eaves shorter than those of Shin's temple buildings, none of its angles fell within the ranges that Shin had specified; because Shin's sample contained no houses, proportions derived from temple buildings should be checked before being applied to houses, and since published models are often stylized, they do not always match the actual measured proportions. The printing process also showed what a desktop printer can achieve at this scale: the columns, the railings and the rows of tiles were printed clearly, while fine strands of plastic are visible beneath the eaves, since these were printed without supports, and the undersides are rough (Figure 4B). It is a geometric model, not a validated structural or thermal model.

A printed model takes a digital file and turns it into a form which people can hold and flip over so as to compare it with drawings. It is useful in museum exhibitions, in classrooms and in engineering workshops since it offers a physical way of examining cultural architecture[31,32].

Figure 5 shows a further print made on the same printer: a published model of the Florence Cathedral which the publisher describes as a "stylized version," having been produced using parametric software from photographs and blueprints

Table 2 The roof proportions given by Shin[38]. and those measured on the file of the printed model (the dimensions in millimeters of that file; section in Figure 3).

Parameter	Shin (61 temple buildings)	Printed model (measured on its file)
Eave height (bottom of column to end of eaves)	Not reported as a single value	31.1 mm
Roof height (end of eaves to bottom of yongmaru)	Not reported as a single value	20.9 mm
Ratio of eave height to roof height	55 : 45 (average)	59.8 : 40.2
Eave angle	24°–35° (average 28°)	6.5°
Roof angle	84°–101° (average 91°)	132.2°
Sum of eave and roof angles	118°–120° (average 119°)	138.7°
Roof slope (end of eaves to bottom of yongmaru)	25°–35° (average 29°)	48.7°
Eave overhang (from column centerline)	1,736–3,341 mm (average 2,577 mm)	3.6 mm at the front of the main hall
Curvature of the ridge (rise of the ridge top above its middle)	Not reported	No rise: the top is 0.6 mm lower at 10 mm and 0.7 mm lower at 20 mm from the middle, and back at the height of the middle at its ends

Table 3 The main dimensions of the printed model. All of them were obtained from the model file and not taken from a drawing or a photograph of an actual building. The print dimensions are calculated by multiplying the model dimensions by the print scale, which is 0.893.

Item	Model file (mm)	Print (mm)
Overall length × width, including the eaves	121.6 × 87.4	108.6 × 78.1
Walls and columns at mid-height: length × width	105.6 × 71.5	94.3 × 63.9
Height from base to the top of the ridge ends	62.1	55.5
Bays and bay spacing between column centers	Main hall: 1 bay along the front (44.2); wings: 1 bay across (28.0; 28.9) and 3 bays along the outer side of the right wing (24.9 + 17.8 + 25.2)	39.5; 25.0; 25.8; 22.2 + 15.9 + 22.5
Columns: diameter × height above the foundation stone (12 free-standing columns)	3.3 × 31.0 to 32.6	3.0 × 27.6 to 29.1
Foundation stones: width across flats × height (hexagonal, tapered)	4.8 (top) to 5.2 (bottom) × 2.7	4.3 to 4.7 × 2.4
Walls: thickness	0.7 to 1.4	0.6 to 1.2
Beams, purlins, and rafters	Not modeled: the roofs are solid, with tile rows on their surface	—
Eave overhang from column centerline (main hall front / wing outer side)	3.6 / 6.4	3.2 / 5.7
Scale	Not stated by the designer	0.893 of the model file

"to ensure printability"[43]. In contrast, the real dome has been measured, a laser scanning operation having recorded its inner surface in 2006 and the data obtained from this scan later being used to establish the scale of a photogrammetric model created in 2014[44]. Even though the print enables people to hold and turn the cathedral together with its bell tower, it is a design model and not a measured record, which is why the source is given in the caption, as required by the London Charter and the Seville Principles[34,35]. Like the hanok model, the print conveys the appearance of the building, whereas its measured geometry, as at Leicester Cathedral, exists only in the survey records.

The situation also raises questions about access. Even the most detailed record does not always prove to be the most usable one; in the case of the cathedral, the point cloud was given to the client in the form of an archive record and the case study does not state whether the public has access to it, while the drawings and photographs from the hanok are included in an open-access article (Table 1). As for private houses, a practical question for future work is to determine who will be in

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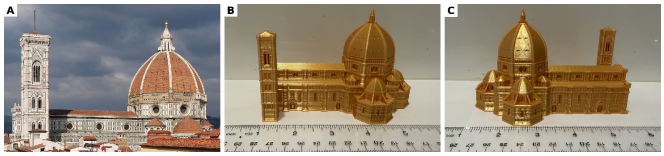


Figure. 5 Florence Cathedral and a published design model of it. A) The cathedral, featuring Brunelleschi's dome and Giotto's bell tower. Photograph (cropped): "Cattedrale di Santa Maria del Fiore Florenz März 2014" by Felix König, from Wikimedia Commons (https://commons.wikimedia.org/wiki/File:Cattedrale_di_Santa_Maria_del_Fiore_Florenz_M%C3%A4rz_2014.jpg), licensed under CC BY 3.0 (https://creativecommons.org/licenses/by/3.0/). B, C) The model was printed on the same printer as the hanok model, with no alterations made to its shape, and is viewed from the same side as in A (B) and from the opposite side (C), together with a ruler; it is stylized and is not a measured survey. Model: "Florence Cathedral, Italy" by MiniWorld3D, originally created by Dany Sánchez (MiniWorld3D (original model by D. Sánchez). Florence Cathedral, Italy (3D model). Printables. https://www.printables.com/model/272943-florence-cathedral-italy, 2023.), licensed under CC BY-NC-ND 4.0 (https://creativecommons.org/licenses/by-nc-nd/4.0/). Photographs by the author.

charge of gathering the digital records, who will pay for them, and who will be responsible for keeping them, as well as how owners, architects, and researchers can share them.

Alternative Technologies for Preservation

Even though 3D printing is significant, there are other modern technologies which also offer a great deal of help in the area of architectural preservation. Table 4 compares these technologies with hand measurement, laser scanning, and 3D printing in terms of accuracy, equipment cost, the skills required, and the kinds of situations they are suitable for.

The full cost of each of these methods includes four elements: the equipment, the software licenses, the time required to carry out the task, and the cost of data storage. As the figures for these expenses have not been given for the two cases examined (Table 1), the only actual figures available in this study are those concerning the printer used in this instance—a consumer-grade printer, free slicing software (UltiMaker Cura), approximately 78 g of PLA, and about 15 hours of printing time—compared with the professional scanner and software used at Leicester[2]. In order to make a complete cost comparison it would also be necessary to know how much time was spent on surveying and modeling, a piece of information which is not included in either of the case reports.

The tools mentioned here supplement 3D printing, and the decision as to which one to use will depend on who is going to use the record, what they expect to learn from it, and how much they can afford.

Solutions and Strategies for Preservation

Cultural heritage must be protected by combining digital and physical methods. First, research into historic design—for example, the roof proportions—helps to ensure that digital reconstructions stay true to the original design of the building, not merely its appearance.

Second, if tools are chosen that non-specialists are able to use and afford, a greater number of students, teachers, and community groups will be able to get involved in preservation. For example, UltiMaker Cura, Tinkercad, and Blender are free, whereas Fusion 360 is only free for personal and educational use; 3D printing can also produce physical models in a relatively short amount of time and usually at a low cost[33]. If the preservation tools are designed with the people who will be using them in mind, rather than with the most advanced equipment, the technologies can be moved out of specialist laboratories and into schools and communities.

Third, by combining scanning with other recording and visualization methods such as photogrammetry, LiDAR, AR, and VR, it is possible to create digital archives that record both shape and context. Indeed, just as much importance should be attached to organizing these records so that people can find and understand them as to collecting them.

Finally, collaboration between engineers, architects, designers, historians, and local communities can help ensure that projects take into consideration cultural values and traditional knowledge. Exhibits that combine physical and virtual models can inspire the public to take an interest in heritage and assist in its preservation.

Limitations

A disadvantage is that most of the findings from this research are qualitative. For example, the costs of the tools were compared qualitatively and a detailed cost analysis was not carried out. The second limitation concerns the scope of the study: the comparison is restricted to just two buildings, and these buildings are not similar since they differ in respect of ownership, statutory protection, funding, size, and type, which means that it is not possible to distinguish between national effects and individual case effects and therefore the conclusions reached only apply to these two buildings. The sources also do not give any information about the cost, the amount of data, or the number of working hours for either of the projects. The hanok model is a published model and not based on a real building that has been surveyed; it also has no stated real-world scale, so it could be compared only with published proportions rather than with a building that has been physically measured, and

Table 4 The typical accuracy, equipment cost, required skills, and best applications of documentation and presentation technologies.

Technology	Typical accuracy	Equipment cost	Skills needed	Best suited for
Hand measurement and drawings (existing)	Not quantified; subject to human error [15]	Low [15]	Measuring and drafting	Plans and details of small buildings; time-consuming [15]
Terrestrial laser scanning (existing)	About 3–6 mm in the surveys cited here [2,19]	High: professional scanner and software [15]	Surveying and point-cloud processing [15]	Complete, accurate records of large or complex buildings, such as Leicester Cathedral
Photogrammetry (camera or drone)	Lower positional accuracy than laser scanning in the survey cited here [19]	Low: ordinary digital cameras are inexpensive [13]	Photography and complex processing [15]	Surfaces, textures, and roofs that ground-based scanners cannot reach [19]
Phone or tablet LiDAR	Within a few centimeters of laser scans [17,18]	About EUR 1,100–1,700 for the device [17]	Little training	Quick surveys of objects with simple shapes [17,18]
AR and VR	Not a measuring method; depends on the source model	Not quantified in the cited sources	3D content creation and programming	Remote access and education [27,28]
Digital twin	Depends on the survey data it is built from	Not quantified in the cited sources	Data integration and monitoring	Preventive conservation of a specific building [29]
3D printing (desktop, as in this study)	Sub-millimeter to millimeter deviations in tests [33]	Low: a consumer printer; this model used about 78 g of PLA	Mesh preparation and slicing	Physical replicas for teaching and museums [14,32]

only through the use of ratios and angles; no structural or thermal analysis was carried out. The roof proportions are based on a single study, and in that study all 61 buildings are temple buildings, so their suitability for houses has not been tested. Finally, the review relied almost entirely on English-language sources and did not examine the Korean-language literature on hanok design and heritage documentation.

Conclusion

In the case of the two buildings examined, 3D scanning was able to capture accurate 3D geometry as well as hidden spaces, which the drawings and photographs of the hanok did not fully record. Digital records can store the dimensions of a building and be used to produce replicas for teaching. The 3D scanning and BIM work carried out on Leicester Cathedral shows how far such records can go in preserving details. On the other hand, the Samcheong Hanok, which was renovated without carrying out a 3D survey, had drawings and photographs but no 3D record of its exact geometry. These conclusions apply only to the two buildings that were studied.

The stylized hanok model that was published had a considerably steeper roof and much shorter eaves than Shin's temple buildings, so none of its angles were within the ranges that Shin had stated; because Shin's sample contained no houses, proportions derived from temple buildings should be checked before being applied to houses, and one should not assume that published models adhere to those proportions. The model was successfully printed using PLA on a consumer-grade 3D printer. As a speculation going beyond the results of this study: if digital records and printed models are designed with the people who use them in mind, they could help more students, visitors, and owners of old houses to see, touch, and care for their heritage, as well as support teaching and disaster recovery; however, this study did not test these applications.

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