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Handcrafted Reproduction of a 17th Century Bema Door Supported by 3D Digitization and CNC Machining

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Abstract: During the Ottoman period, wood had replaced marble in Orthodox churches. Between the 16th and 19th century, common, unknown craftsmen created wonderful wood-carved ecclesiastical works by hand, though many of them have been partially or completely destroyed, usually without any of their images being saved. Advances in technology now make it possible to develop a detailed digital copy of an object of our cultural heritage, creating an unaltered prototype material to be studied by all, while offering in parallel the ease of reproducing precise copies, ensuring even museum quality standards. In the present study, a corresponding attempt to record, scan and then reconstruct a 17th century "Bema Door" (located in the Holy Monastery of Hilandar in Mount Athos) is implemented, presented step-by-step and discussed, in order to highlight the challenges and potential of the applied methods. The process included on-site recording of a 3D digital scan, and then the creation of the Bema door copy, first applying Computerized Numerical Control (CNC) machining and then, with elaborate handwork by experienced wood-carvers who successfully completed the process, imparting the necessary and unique human artistic character. The current work transfers the experience on this reproduction technique applied in a Bema door element, shares significant information and details on tools, materials, process steps, etc., in order to be an inspiration and stimulus for the preservation or reproduction of other cultural heritage monuments of high importance.

Keywords: ancient; artifact; carving; culture; digital; gild; heritage; reconstruction; reproduction; structure; wood

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1. Introduction

Wood, among its several advantages compared to other materials, is an aesthetically incomparable material, presenting a wide variety of colors, textures and designs, and in addition, it is easy to join and accept varnishes or paints, while its processing can be implemented even using only basic tools. It is certainly reasonable to say that all of these advantageous characteristics have contributed to its widespread application since prehistoric times and it has served as the fundamental material in a wide range of applications since then [1].

During the Byzantine era, the use of wood in Orthodox churches was typically found only in their different portable objects. However, during the Ottoman period wood replaced marble and became the main material used in the interior decoration of Orthodox churches. The economic power that began to appear in the enslaved Greek population from the 17th century on, with the development of trade and the production of certain special products, was reflected, better than in any other expression of social life, in the construction of new houses, mansions and especially new churches, when the Ottomans allowed them to be built [2]. Since the conquerors imposed the external appearance of these churches to be more humble and poorer compared to the mosques, the believers put emphasis on enriching the interior decoration of their churches with magnificent wood-carved structures. Therefore, the artisans had the chance to display all their artistic skills in the interior decoration and to provide them with a distinctly imposing and reverential atmosphere inside the churches, with the wooden iconostases being the most important jewels of these churches.

Monastic complexes and villages that had acquired privileges from the Ottoman power became important centers of artistic wood-carving activity since the 16th century [3]. Residents of certain villages of Epirus and West Macedonia had been specialized in wood-carving and they had undertaken the decoration of churches in Greece as well as in many Balkan countries [4]. These ordinary, unknown carpenters, usually working under very tough conditions though with passion and a high sense of aesthetics, created wonderful wood-carved iconostases and other ecclesiastical objects by hand from the 16th to the 19th century. These authentic works of folk art made of wood nowadays constitute unique cultural heritage monuments of the post-Byzantine period.

However, in addition to its many benefits, wood also presents a number of drawbacks. As a lignocellulosic, biological material, it can burn or rot, and when it absorbs moisture it becomes more vulnerable to attack of bacteria, fungi and insects [5]. Taking into account the aforementioned disadvantages of wood, mainly resulting from its biological nature, combined with the environmental conditions prevailing in Greece that are favorable to its biological degradation, as well as the high number of wars and lootings that the country has suffered from in the past, it is not surprising that the archaeological findings concerning wooden objects and structures in Greece are really few [6]. Even the magnificent iconostases and other wooden artifacts of the post-Byzantine period did not remain unharmed by the impact of gradual deterioration. Many of them have been completely destroyed, with the loss of some valuable works of art of the past, usually without even a single image of them being saved, resulting in a great loss to civilization. Additionally, those that are still preserved have suffered varying degrees of damage, and there is always the risk of their partial or total destruction and loss [7]. The access to and study of these valuable wooden objects of cultural heritage is, most of the times, difficult or even impossible for ordinary citizens, as well as for scientists who are not involved in the field of archaeology. This difficulty applies in cases when they remain in their original places of installation, but also when they were transferred to museum spaces.

Nevertheless, even humble works of art reflect the culture of people, and humanity should consider them as a common heritage of all. Therefore, we have a duty to preserve them and pass them on to future generations, preserving all their richness and authenticity. Therefore, effective and active measures should be taken to protect them, since cultural heritage is increasingly threatened by destruction, unfortunately not only by the common causes of deterioration [8].

Nowadays, the development of technology makes it possible to create a detailed digital copy of a monument of our cultural heritage, thus generating an unaltered study material for all, but also offering ease in the production of precise copies of them [9,10]. Currently, the E.U., in the Horizon Europe program, funds the Cultural Heritage Cloud initiative which aims to add a new digital dimension to the preservation, conservation, restoration and enhancement of cultural heritage by providing cutting-edge technologies for the digitization of artefacts and the research of works of art [11].

Digital technologies have been adopted in various fields related to the museum experience and digital preservation, as well as the digitization and study of archaeological artifacts [12]. In fact, over the past decade technological advances in the fields of portable electronics have revolutionized the use and range of applications of tablet computers, smart phones and mobile devices [12]. With these opportunities provided by the ongoing technological advancement, academics have considered several techniques to create more accurate and convenient 3D digital copies of cultural heritage items of value.

For the continuous 3D scanning of small- and medium-sized heritage objects, Kesik et al. [13] proposed the "3DScaMOTO" methodology that achieved scanning results of good quality. A handheld Artec EVA 3D scanner (Senningerberg, Luxembourg) with structured light was used for the scanning, which offered precision of 50–100 microns and preserved photorealistic texturing. This methodology would contribute to successfully overcome scanning challenges such as an object being movable but with a glossy surface, an object being not movable but of good accessibility, and at last, an object being not movable combined with bad accessibility. Kochov and Stoleska [14] described the methodology they applied to the woodcarving digitization and reproduction process through practical examples. The creation of the digital copy of one wood-carving was implemented using NextEngine 3D Scanner (NextEngine, Santa Monica CA, USA), while the other two were created using the principle of photogrammetry together with the AutoDesk ReCap program v.23.0.0.258. The reproduction of the wood-carvings was carried out using Computerized Numerical Control (CNC) machines ("Uniteam professional 5 axis", Uniteam, Grgar, Slovenia), as well as 3D printing, while mentioning the cost of equipment and materials. Specifically, they developed a methodology that constitutes an example of reversible engineering for wood-carvings: the digitalization is implemented with one of the available tools, the carving is being "cleaned" in one of the programs found easily on the market, then the section is transferred to appropriate CAD/CAM programs and the 3D printer and/or CNC machine are allowed to do the "magic" work, which constitutes a fusion of engineering with art that is of great historical and cultural importance. Učakar et al. [15] created 3D graphical representations of wooden sculptures with photogrammetry (converting photos into 3D digital models) that were used for 3D printing reproduction, jewelry production, etc., while stating that the new technologies cannot replace real works of art, but that 3D representations offer significant help to conservators and, in addition, allow us to preserve at least the cultural and historical values of those art objects that cannot be preserved for various reasons. Neamțu et al. [16] presented the methodology applied in the digitization and digital restoration of imperial gates from wooden churches in Transylvania, to show the degradation of these cultural heritage objects over time. The procedure for digitally restoring the object to its pristine state included X-ray fluorescence (non-destructive elemental analysis (XRF) with a handheld Bruker spectrometer), FTIR spectroscopy measurements (with a Jasco 6100 spectrometer, Easton, MD, USA) and scanning and digitization using a Creaform Go!SCAN 50 structured light scanner (Go!SCAN, AMETEK, Bangkok, Thailand). Carvajal et al. [17] used the Mu3D digitization system based on digital photogrammetry to create virtual museums, applying digital photogrammetry and computer 3D modeling. They concluded that the same virtual environment can be arranged either for different collections or the same collection in a different layout that fits different groupings of objects that respond to different contexts, uses and users.

For the copyright protection of 3D digitized works of art, it is proposed, by Vasiljević et al. [18], to add some unique local indistinguishable errors, so that in case of any misuse of the 3D model with digital error, such as if someone would try to print a 3D model of this sculpture, the authors who made the sculpture available to the public could easily determine the originality of any copy of the sculpture that appears anywhere in the world.

Ramm et al. [19] presented a method they had developed for in situ high-resolution 3D digitization of cultural heritage objects, with a strong focus on portability. The digitization system consists of a 3D structured light sensor module, a connected DSLR camera and a data processing software on a separate workstation, with the workstation being recommended to be a laptop so that the entire system is portable.

Adamopoulos et al. [20] compared the quality of 3D digitization of cultural heritage objects from a variety of photogrammetric software, as well as photo-capturing equipment of various characteristics and prices and scanners of various technologies.

The digitization of exhibited objects, together with the digitization and information enrichment of the museum building, provides the possibility to improve the conditions of management and enjoyment of the museum, such as making a part of the heritage that is not accessible so far accessible to the public through the virtualization of the exhibits stored in the repositories [21].

The aim of the current work is to investigate the possibility of reproducing a precise copy of a wood-carved object of medium size and considerable cultural value, which may continue to be in its place of use or be exhibited in a museum space, taking advantage of the possibilities offered by the development of digital technology through 3D scanning, combined with traditional wood-carving handwork. The applied methodology is discussed in terms of advantages, challenges and future potential utilization.

2. Materials and Methods

For the purposes of this study towards the creation of a precise copy, a unique Bema door characterized by rich wood-carved decoration, was used as the model object (Figure 1).

Figure 1. View of the Bema door dated from 1615 AD found in the museum area of the Hilandar Monastery of Mount Athos.

Specifically, the particular Bema door constitutes a part of an iconostasis, constructed in the year 1615 and belongs to the Hilandar Monastery of Mount Athos (Figure 2), which only a few people have access to, as there are several restrictions on the access to Mount Athos (northern Greece) and the respective monasteries, whereby women are not allowed access at all. The main aim of this project was the reproduction and creation of a precise copy of this original Bema door, which at the moment is exhibited in a museum of the Hilandar Monastery.

The Bema door consists of two door leaves, which, in addition to the impressive and dense carving they contain, are also decorated with additional high-relief decorative parts, also of similar rich carving, which protrude considerably from the surface of the door leaves and are attached to them using adhesive, as well as the semi-cylindrical "astragal" placed at the junction of these two door leaves. The Bema door also includes flat sections covered by painted decoration. Its dimensions are approximately 150 $\times$ 105 cm, with its upper side having an arched shape [22]. The wood-carving of a Bema door leaf is considered shallow by wood-carvers when the depth of the carving does not exceed 2–2.5 cm, as is the case for this specific Bema door. An important feature of the Bema door is the gilding that has been applied to its entire surface. Gilding is a treatment applied, mainly for aesthetic reasons, to wood-carved objects after the completion of their construction, offering to them an impressive appearance, though it can alter the original details of the wood-carving to a small or large extent due to the several coating layers applied. In particular, the gilding, as described in detail in an 18th century manuscript, included the following individual stages [10,23]: (a) the production of animal adhesive, using this for coating of the wooden structure (mixed with water) and rubbing it with a brush for better penetration into the deeper parts of the carvings; (b) mixing gypsum plaster with water and adhesive, followed by coating using a brush (five–six layers) and sanding to smooth any irregularities; (c) the construction and coating of two or three layers of "bole", i.e., a mixture of clay and other materials (ochre or constantinopolitan ochre, mercury, soap, egg white, etc.), different depending on the case and the desired color; (d) spreading the surface with raki (using a sponge, soft brush or cotton) and, finally, carefully placing the layers of gold. It is logical that these multiple coating layers on the wood-carved Bema door adversely affect the process of producing a precise copy of it.

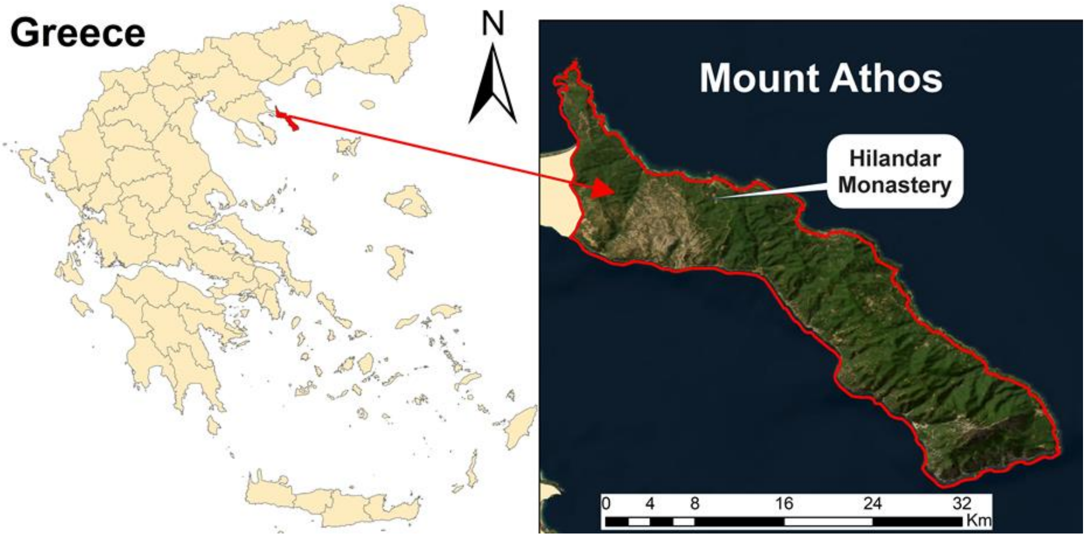

Figure 2. Location of Hilandar Monastery on the Holy Mount Athos Peninsula.

Identification of the wood species that the specific Bema door is originally made of has not been implemented so far. Verbal estimations indicate the possibility of it being made of walnut wood. However, it should be mentioned that in Greece there is no wooden object of archaeological and cultural value, exhibited in museums, with any relevant reference to the wood species.

For the scanning process, a portable Artec Space Spider 3D Scanner (Figure 3A) was used, which is based on blue light technology and is ideal for capturing small objects or complex details in high resolution. All the work of scanning and final sculpting was carried out by a family wood-carving business (Thessaloniki, Greece). Multiple scans were obtained from different directions in order to capture all the features, and then a point cloud was created, which was processed using a special CAD (Rhinoceros 5) and CAM (Rhinocam 2015) software to produce a precise 3D digital copy (Figure 3B), in order to be used in the machining in an automated way, by means of a CNC machine, a key part in the process of reproduction of a wood-carved copy of the original Bema door that followed. The final digitization processing was implemented using the Uniterm 3D modeling Rhinoceros 5 commercial software. The 3D model generated by the scanner initially corresponded to a 2 GB file (which was decreased to 180 MB in the following, to be more easily processed) with 0.015 mm initial accuracy (in the following the accuracy was decreased to 0.05 mm for the same reason). Smoothing and abnormal triangles filter options were applied during the process. The reverse engineering software "Geomagic Design X" (version 2015) was used for the filling of gaps and holes in the scanned 3D model. There were indeed specific gaps in the scanning results, attributed to the given conditions of the scanning process (limited time; location, since it is permanently exhibited in a monastery museum room; and other difficulties and limitations in the scanning process primarily brought about by the monastery). A resampling process was not applied given the circumstances of limited time and access to the exhibition place of the Bema door.

(**A**)

(**B**)

Figure 3. Scanning process of the original Bema door (**A**) and digital scan result (**B**).

It should be mentioned that since the current stage of copy production of the Bema door involved the wood-carving of only the parts of it that are on the surface of its main wooden body, all the additional decorative wood-carved elements attached to it were removed from the digital copy. The scanning duration for the whole Bema door was about 8 h (1 day), while the processing time of all these scan data (until the reproduction phase in CNC was ready) was about 1 week.

The CNC machine used for mechanical carving was a ROVER K type (Biesse, Pesaro, Italy) with the following characteristics: the number of controlled axes was 3, the total number of drilling spindles 16 and the total number of tool changer positions was 16. For the machining of the specific Bema door, 2 machining drill bits were used, 12 mm in diameter, with a step of 3 mm for the initial rough machining and 1.6 mm in diameter with a step of 0.4 mm for the elaborate work of the details.

In order to reproduce the Bema door, lime wood (*Tilia cordata*) was initially used, which is light in color, has a fine and even texture and is soft enough to carve while being resistant to tearing [24]. Its ease of processing, which derives from these favorable characteristics, contributes to its classification as one of the most popular wood species intended for carving, as noted already during the Middle Ages [25]. However, the Greek philosopher Theophrastus (371–287 BC) mentioned in ancient times that it was known that the wood of lime trees is the most refined and easily processed of all wood species (*Historia plantarum*, V, 5-1). For this reason, lime constitutes the most popular wood species chosen by beginners in wood-carving. It should be noted, however, that lime wood is not resistant to biological attacks [24]. More specifically, according to the EN 350 standard [26], it is classified in class DC 5 as non-durable to fungal attacks and in class S as of low natural durability and being susceptible to termite attacks and action. Therefore, this wood species is not recommended to be used in high-value constructions such as iconostases. Nevertheless, in this particular case, the reproduction was first carried out with the soft lime wood in order to render the carving of details more accurate and easy, while in the second stage, a wood species of higher density and hardness was used. In both cases of wood species, for the construction of each Bema door leaf, wood boards of 10–12 cm width were used and were glued together using D3 PVA adhesive (AKFIX, Riga, Latvia).

In particular, the process of reproduction began with carving on the CNC machine and then the "rough" result of the mechanical carving was corrected and further improved by hand-made work carried out by experienced wood-carvers. The resulting new lime wood-carving was then scanned again, following the same process as the scanning of the original object. By scanning the copied object in a laboratory infrastructure this time, the opportunity for a more detailed and cleaner recording of its sculptural details was provided. Since the new 3D digital copy resulting from the scan required additional processing and shaping because of its adjustment to a new iconostasis, it was decided to make the wood-carved copy of a different, smaller width (by 10 cm) compared to the original one. Additionally, since the original Bema door was gilded and, thus, had various layers of materials on its surface, the digital copy was cleaned and corrected thoroughly in its various decorative patterns, a step which requires experience and deep knowledge of the use of designing and reproduction programs.

Oak constitutes the oldest wood species that is widely known to be used in wood-carving, especially the species *Quercus robur*. Oak wood is hard and has an attractive brown color with a smooth and shiny surface and very beautiful grain pattern known as "silver grain". It is a good choice of wood species for use by experienced wood-carvers, though, because of its hardness, it is not that suitable for beginners. Its sapwood part is very susceptible to insect attacks, while its heartwood is considered very durable under any conditions [27]. According to the EN 350 standard [25], it is classified in class DC 2 as "durable to fungal attack" and in class M as "moderately durable" concerning the natural durability against termites' action; therefore, it is widely used in wood-carving elements of high value, such as construction of iconostases.

At the end of the reproduction process, the Bema door copy made of oak wood was cautiously sanded using No 120 and 150 grain sandpapers to smooth the surfaces, and then the whole copy of the Bema door was disinfested by being exposed to phosphine. The next step to follow was the process of gilding, leaving only the flat areas intended to be painted vacant (iconography creation).

3. Results and Discussion

The CNC machining of the lime wood resulted in the overall appearance of the wood-carving, it bearing all the embossed features of the original Bema door, but with the surface quality being quite rough and without the final depth of carving achieved, details which are necessary since they enable the wood-carver to process it (Figure 4).

Figure 4. Detailed view of the CNC machining process of the lime wood.

Moreover, due to the gilding that exists on the original Bema door, many of its wood-carved details had been blunted to some extent. Since gilding was to be applied to the final copy of the Bema door in one of the next stages, it is evident that, by preserving these faded features of the original gilded Bema door in the final gilded copy as they were, there was a possibility that many of its wood-carved details would no longer be apparent. In addition, in an old wood-carving over 400 years old, such as the studied one, there will certainly be some micro-cracks or other alterations/deteriorations of the material surface and probably of the design/shape. The handmade work that followed resulted in the highlighting of the details of the wood-carving and refining of its surface configuration (Figure 5).

Figure 5. Detailed view of the finishing work on the lime wood implemented by wood-carvers' handiwork.

It is worth mentioning that the processing of the high-relief decorative parts of the Bema door was separated from the shaping work of its superficial wood-carved parts, which preceded it (Figure 6). Moreover, in the original Bema door all its high-relief parts are added and glued on the surface of the Bema door leaves.

Figure 6. Refinement of the wood-carving in the lime wood after applying handiwork by wood-carvers.

The completed Bema door that resulted from the processing of lime wood was a precise copy of the original one (Figure 7) and constituted the new model item for the construction of the final copy in oak wood. This new final model, now given the convenience of time, laboratory infrastructures and controllability potential of the result, was scanned in detail in order to be able to use the new digital copy for the CNC machine to produce one or more copies using any wood species desired. In this particular case, as mentioned, oak wood was chosen since the copy is to be used in an iconostasis, in a similar place to that of the original Bema door. The lime wood copy could be used as an exhibition piece, though, due to its low biological resistance and hardness, it is not recommended for any functional use.

The new digital copy could also be used for the production of copies using a 3D printer, especially in smaller dimensions or the reproduction of individual parts of it, which could be made available for sale for the financial support of the monastery.

Figure 7. Details of the original gilded Bema door.

The CNC-machined oak wood-carving (Figure 8) was improved and refined in its carving details by hand-crafting by an experienced wood-carver (Figures 9–11). Human contribution is particularly important, since it is the part that provides the final details' configuration to a wood-carving and, moreover, the appearance of a hand-made wood-carving piece similar to the original one. During the reproduction process, an attempt has been implemented, in order any potential signs of destruction, wear or tear caused to the original Bema door during its 408-year life (since the construction year) were not reproduced.

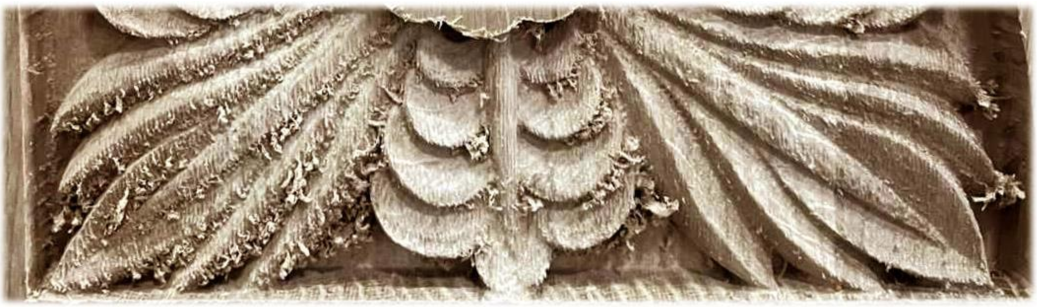

Figure 8. View of the CNC-machined wood-carving details in the oak wood.

Figure 9. View of the refined by wood-carvers' wood-carving details in the oak wood.

Figure 10. Copy of the whole Bema door leaf (**left**) made of oak wood and the whole image of the final version of the Bema door copy in oak wood bearing all the attached decorative parts (**right**).

Figure 11. A pattern of the original gilded Bema door (**left**) and its corresponding copy in oak wood (**right**).

The refining of the piece is always conducted by removing material from the main wooden substrate by wood-carvers. If there are several missing parts in the original artwork (here only few missing parts were detected), they are usually digitally corrected during the 3D model creation process, prior to the manufacturing. Sometimes this process is implemented while also taking into account previous evidence, such as images or drawings of the initial design, the logical continuity of the design or similar patterns found replicated in different places on the same art-piece, etc. The wood-carver contributes significantly to this work as well, and especially, does not leave any destroyed or missing points/parts without the necessary correction, based again on the initial design of the original work.

The wood-carving tool traces do not constitute a problematic issue, rather a desirable one that, of course, cannot be precisely replicated (even by the same wood-carver), although the tools used in wood-carving have been more or less the same for thousands of years. In general, the wood-carver in the last step of reproduction process bestows it with this special unique appearance of the handmade work. The contribution of the human factor (the wood-carver's view and artistic skills) may have slightly varied some curves or other points, always respecting the initial design and detailed images of the original Bema door elements.

The reproduction of precise copies of old wood-carved icons or parts of them, exclusively in the traditional way, is a very difficult process, as it requires many hours of laborious specialized work of an experienced and talented wood-carver and correspondingly, very high cost [28]. The machining, combined with the digitization of the original object and the correct reproduction of the wood-carving patterns in the produced copy, contributes significantly to the reduction in the wood-carver's working time and the corresponding total cost of reproduction [28]. Of course, the level of resolution and choice of material determine the final cost of the copy as well [29].

Particularly, for each of the two leaves of the Bema door, the machining process on the CNC machine lasted about 7 h (keeping in mind the step of 3D digitization that lasted 4 h for each leaf and the scanning data processing that lasted one week for the whole Bema door), followed by four more days of manual work by the wood-carvers to refine it. Without the CNC machine, applying only the manual wood-carving, it would take twice as long.

In the present project, the enormous importance of the coexistence of human contribution and CNC machine involvement towards a successful, easy, quick and of low-cost reproduction of high cultural value and heritage wood-carvings was highlighted.

4. Conclusions

From the 16th to the 19th century, unknown folk craftsmen without special education and working under very difficult conditions, created, by hand, amazingly designed and beautiful wooden church objects, which are unique cultural heritage monuments of the post-Byzantine period. The chemical composition and biological resistance of wood, combined with many other unfavorable factors led to the destruction or significant degradation of many of them. Additionally, the access to these valuable wooden objects of cultural heritage is often difficult or even impossible for the general public.

The development and application of 3D imaging in many fields has motivated many researchers to study the utilization of the potential of this technology in the field of cultural heritage. Three-dimensional (3D) digitization can be used in a variety of ways, such as in the production of digital files, remote study, but also to create precise copies of various constructions, contactless and with great precision.

Digital files combined with mechanical processing now offer a unique opportunity to reproduce precise copies of old wood-carved elements or parts of them faster and more economically than the traditional way which is a very difficult, laborious process, as it requires many hours of specialized work and consequently, a very high cost. The location or size of the original wood-carving were not proven to be a restriction.

The reproduction, in slightly smaller dimensions, as required of an exhibition gilded, wood-carved Bema door from the 17th century carried out in the context of this work, was based on the modern technology of digital copying and machining, while it was completed with hand-made processing by an experienced wood-carver, thereby providing an excellent detailed result in copying its wood-carved designs, as well as the appearance of a hand-made result, such as the appearance of the prototype, while significantly reducing the total time of wood-carving work.

For the successful completion of such a project, the choice of suitable wood species for each step during the reproduction of copies (lime and oak) was of high importance, and, therefore, the in-depth knowledge of each wood species' properties and performance, as well as the excellent knowledge of the digitization, use of scanning design programs and the mechanical equipment for the wood processing. Finally, it seems to be a matter of utmost importance to support and preserve the "woodcarver" profession, as well as provide proper training to future wood-carvers, during which the thorough knowledge of wood structures and properties should play a prominent role, in order to contribute to the preservation of such high-value monuments and artifacts, through reproduction of high accuracy.

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Conflicts of Interest: Author George Economidis is employed by the company "Xilogliptiki-Wood Carving-Emilios Ekonomidis & Sons". The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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