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Review

3D Scanning/Printing: A Technological Stride in Sculpture

G.-Fivos Sargentis [1,*], Evangelia Frangedaki [2], Michalis Chiotinis [1], Demetris Koutsoyiannis [1], Stephanos Camarinopoulos [3], Alexios Camarinopoulos [3] and Nikos D. Lagaros [4]

1 Laboratory of Hydrology and Water Resources Development, School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zographou, Greece; mchiotinis@mail.ntua.gr (M.C.); dk@itia.ntua.gr (D.K.)
2 Department III, Architectural Language, Communication and Design, School of Architecture, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zographou, Greece; efraggedaki@arch.ntua.gr
3 RISA Sicherheitsanalysen GmbH, Xantener Straße 11, 10707 Berlin, Germany; s.camarinopoulos@risa.de (S.C.); alexios.camarinopoulos@risa.de (A.C.)
4 Institute of Structural Analysis and Antiseismic Research, School of Civil Engineering, National Technical University of Athens, Heroon Polytechneiou 9, 157 80 Zographou, Greece; nlagaros@central.ntua.gr
* Correspondence: fivos@itia.ntua.gr

Abstract: The creation of innovative tools, objects and artifacts that introduce abstract ideas in the real world is a necessary step for the evolution process and characterize the creative capacity of civilization. Sculpture is based on the available technology for its creation process and is strongly related to the level of technological sophistication of each era. This paper analyzes the evolution of basic sculpture techniques (carving, lost-wax casting and 3D scanning/printing), and their importance as a culture footprint. It also presents and evaluates the added creative capacities of each technological step and the different methods of 3D scanning/printing concerning sculpture. It is also an attempt to define the term "material poetics", which is connected to sculpture artifacts. We conclude that 3D scanning/printing is an important sign of civilization, although artifacts lose a part of material poetics with additive manufacturing. Subsequently, there are various causes of the destruction of sculptures, leaving a hole in the history of art. Finally, this paper showcases the importance of 3D scanning/printing in salvaging cultural heritage, as it has radically altered the way we "backup" objects.

Keywords: 3D printing; 3D scanning; sculpture; art; technique; stride of civilization

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1. Introduction

Strides of civilization are connected to technological issues, which have improved the quality of life [1,2], such as the installation of hydraulic works (hydraulic civilization [3]); architectural creations [4]; great technological inventions, which have changed history (e.g., the evolution of wheels [5]); a combination of technological issues, which has created a remarkable duration of social stability (e.g., Minoan civilization 3000–1100 BC [6–8]); and admirable technological creations, such as the Mechanism of Antikythera [9]. However, civilizations are generally characterized by their artistic creations.

The question is why do we have to study art issues? Friedrich Nietzsche (1844–1900) notes that: "The ugly truth is: we have art so that we go not to the underlying truth" [10]. Perhaps what is "true" for an artist is different to the truths of a philosopher or a scientist and represents the spirit of the civilization.

Sculpture is developed by a unique combination of art and technology. Sculpture is a constructive art, and it is dependent on the technological knowledge of each era. In ancient Greece, sculpture was not an "art" but a "technique". Since sculpture needs heavy manual work and muscular power, sculptors were considered as the slaves of art [11]. It is important to note that learning the art of painting was forbidden to slaves in Classical Greece as painting was allowed to noble spirits, contrary to sculpture [12]. Leonardo da

Vinci (1452–1519) had the same perception as he considered that sculpture does not require as much intelligence and causes physical tiredness [13].

However, there is another important characteristic of sculpture. A statue is a prototype. The capacity for the creation of prototypes gives civilization the opportunity to go beyond theory as gives form to abstract ideas in the real world. This creative ability becomes clear if we consider how easy and cheap it is to construct prototypes today [14,15].

Many technological innovations have been made for the creation of big statues, as monumental statues in public space are unique, and each construction demands a different engineering approach. One admirable creation in antiquity, between other colossal statues, is the statue of Ramses II in the first peristyle court at Luxor (1400 BC) (Figure 1a), and in modern times, the Statue of Liberty, designed by French sculptor Frédéric Auguste Bartholdi (Figure 1b). The metal framework of the Statue of Liberty was designed by Gustave Eiffel (Figure 1c). Other impressive huge statues are Six Grandfathers (Mount Rushmore) [16], The Motherland Calls (Mamayev Kurgan in Volgograd, Russia) [17], the Statue of Unity (Narmada District, Gujarat, India) [18] and many more. These paradigms are remarkable and unique technological achievements.

(**a**) (**b**) (**c**)

Figure 1. (**a**) Ramses II [19]; (**b**) Statue of Liberty (1886) [20]; (**c**) interior of the Statue of Liberty [20].

These creations are high-cost, large-scale projects, using many resources (manual work and materials). Therefore, these objects contain important information concerning cultural heritage, as sculptures in public places must be socially accepted, and technological developments, such as specialized technological innovations, have been used to create them.

This paper analyzes basic sculpturing techniques, e.g., carving and lost-wax casting, and their importance as a mark of civilization. Subsequently, it describes the passage and the importance of 3D scanning/printing and emphasizes 3D scanning/printing as an important technological stride. Furthermore, this paper evaluates the added creative capacity of each technological phase.

Three-dimensional scanning/printing is a completely new technique, leaving behind the last innovation in sculpture (lost-wax casting), which was introduced in Classical Greece. This paper presents the dynamic of research in 3D scanning/printing, and shows the importance of prototype creation. It also presents and evaluates the different 3D scanning/printing methods concerning sculpture. However, as 3D printing puts an additional stage (3D manufacturing) between the artist and the observer, we note a disadvantage in this process for sculpture, as material poetics are lost.

Subsequently, various reasons are presented, which lead to the destruction of sculptures, leaving a hole in the history of art, and the importance of 3D scanning/printing is presented for the preservation of art through replicas, providing important opportunities to conserve cultural heritage.

2. The Three Historical Steps in Sculpture Techniques

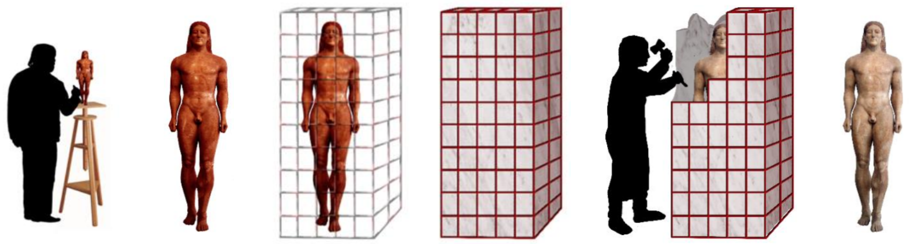
Since prehistory, humans have tried to find and represent the shapes of nature. This ability separates humans from other creatures, as art is a method of communication between a creator and an observer. Creators and observers have a three-fold obligation:

1. Knowledge of the prototype;
2. Profound conception of the representation;
3. Evaluation of the representation.

Generally, sculptors do not make the statue directly in the final material. First, they make the model by wax or clay, and then prepare the model in its final material. As artists have often been known disobedient to the rules or processes, there are many exceptions. In this chapter, we distinguish two common methods for the creation of statues, carving and lost-wax casting, and show the shift towards 3D scanning/printing.

2.1. Carving Method

Figure 2 shows the basic steps of the carving method. The artist makes the model from clay or wax, and after its study, it is made it to the scale the artist wants. After this process, a craftsman finds the 3D coordinates of the artifact and carves the material.



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 2. Basic steps of carving method: (**a**) model in clay or wax; (**b**) scaling of the model; (**c**) measuring process for carving; (**d**) carving; (**e**) final artifact.

2.2. Lost-Wax Casting Method

Figures 3–5 show the lost-wax casting method. The artist makes the model from clay or wax, and after his study, he creates it to the preferred scale (Figure 3a,b). For the next step in this process, a craftsman creates the mold of the sculpture (Figure 3c,d). Subsequently, the craftsman presses wax (7–10 mm) into the mold to make a shell of the same statue in wax (Figure 4a,b). Then, the craftsman installs a network of wax tubes (Figure 4c) that will be the pathways of the outgoing melted wax and metal to fill the empty space without trapping air inside it. In this example, the wax tubes are placed inside the body to lead the wax out, and wax tubes outside the body to lead the metal in (Figure 4c). Normally, both networks are inside the body for a life-size statue.

After that, the craftsmen enclose the wax model in a fire-resistant ceramic mortar (Figure 4d). The mortar is heated to 250–350 °C for 3–15 days (depending on the size of statue), and the wax is melted out (Figure 5a). Metal is casted into the mortar to fill the empty spaces (Figure 5b). The final artifact is finished after the removal of the metal tubes (Figure 5c).

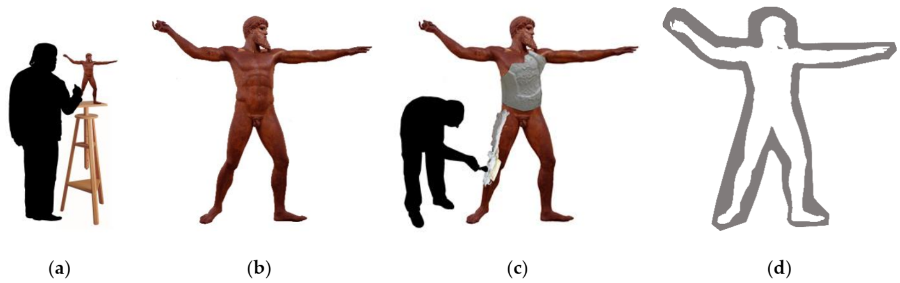


Figure 3. Basic steps of lost-wax casting method: (**a**) model in clay or wax; (**b**) scaling of the model; (**c**) a craftsman makes the mold of the model; (**d**) mold of the model.

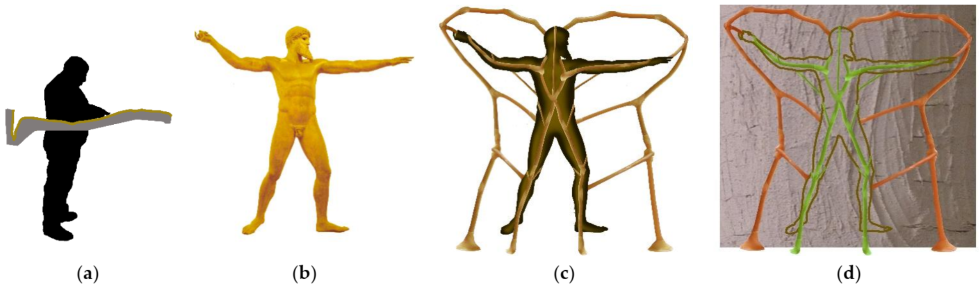


Figure 4. Basic steps of lost-wax casting method: (**a**) a craftsman makes the wax model; (**b**) wax model shell; (**c**) network of wax tubes inside (for the outgoing of the wax in green) and outside (for the entry of metal); (**d**) enclosing of the wax model (including the wax-tubes network) in fire-resistant mortar.

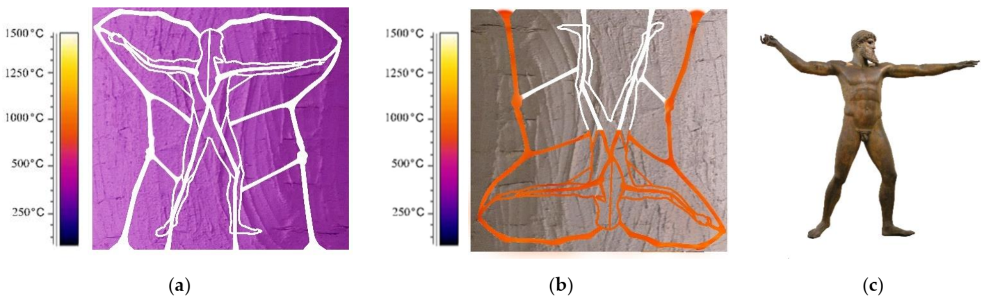


Figure 5. Basic steps of lost-wax casting method: (**a**) the fire-resistant mortar with the wax model and wax-tubes network is heated to 250–350 °C for 3–15 days (depending on the size of statue) and the wax is melted out; (**b**) metal foundry; (**c**) final artifact after the removal of metal tubes.

The sculptures in prehistory were figures carved out of stone or other materials. Humanity passed through the copper age and the iron age, but until Classical Greece, the carving technique was the basic method, especially for large-scale sculptures.

The lost-wax casting method was a great technological step for the creation of large-scale statues [21,22]. Pausanias (8.14.8) noted that: *«διέχεαν δὲ χαλκὸν πρῶτοι καὶ ἀγΆλματα ἐχωνεύσαντο Ῥοῖκός τε Φιλαίου καὶ Θεόδωρος Τηλεκλέους ΣΆμιοι.»* [23] "The first men who melt bronze and cast bronze sculptures were the Samians Rhoecus the son of Philaeus and Theodorus the son of Telecles" in the second part of 6th century BC in the era of the tyrant Polycrates of Samos. A unique illustration of an ancient Greek foundry is depicted on the Berlin Foundry Cup, a Sixth Century BC vase. It portrays the process of creating two large statues at different states of manufacturing [24].

2.3. The Benefits of Lost-Wax Casting

The goal of the lost-wax casting method was that the design was freed from the given material's constraints. Bronze statues created by the lost-wax casting method are not solid, but they are shells of bronze of 7–10 mm in width and are significant lighter. If we consider a marble cube with an edge of 1 m^3, its weight will be 2.64 tons. If we considered the same cube made with lost-wax casting (i.e., 1 cm shell width), its weight would be about 523 kg. If it was a solid bronze object, its weight would be 8.73 tons.

Although every statue is different, the distribution of volumes is stochastic, and the width of the bronze shell in the lost-wax casting process is dependent on the craftsmen who made it; Figure 6 shows the weight of cubes with different edges if they were made using marble, solid bronze or bronze with the lost-wax casting process and the weight ratio between different techniques (4 cube faces).

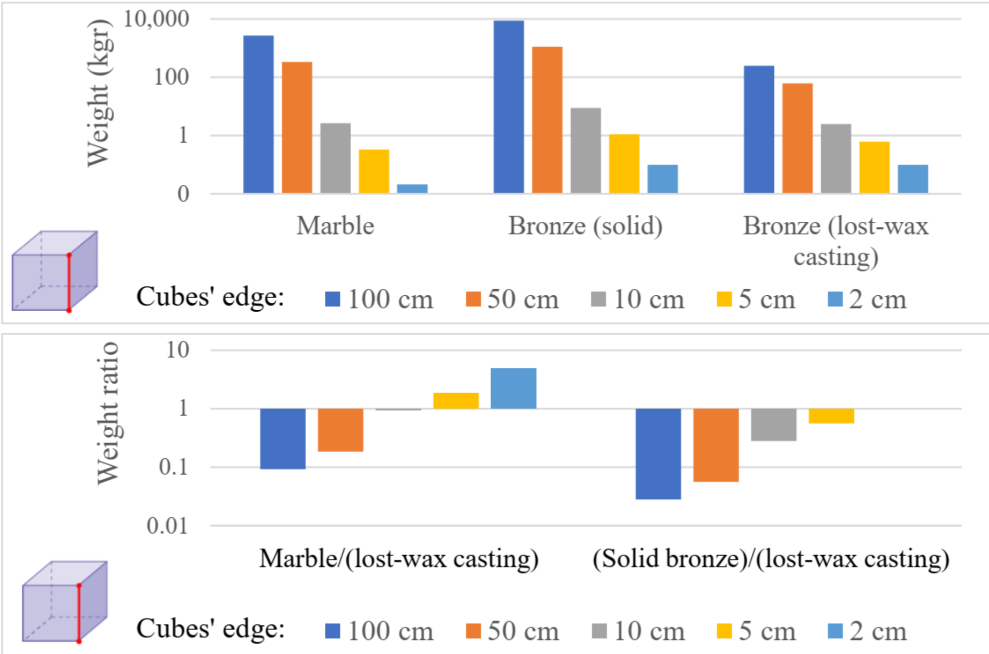


Figure 6. Top: The weight of cubes made from marble, solid bronze or bronze with the lost-wax casting process with different edges; **bottom**: the weight ratio between different techniques (four faces).

With lost-wax casting, artists could create free forms of large-scale sculptures, with intense movement [25] (Figure 7).

It is important to note that for the use of lost-wax casting, knowledge of foundry (technique, geometry and fluid mechanics of molten metal) and the ability to melt a large amount of metal (about 150 kg of metal for a life-size figure) at 950 °C (melting point of bronze) are necessary [26].

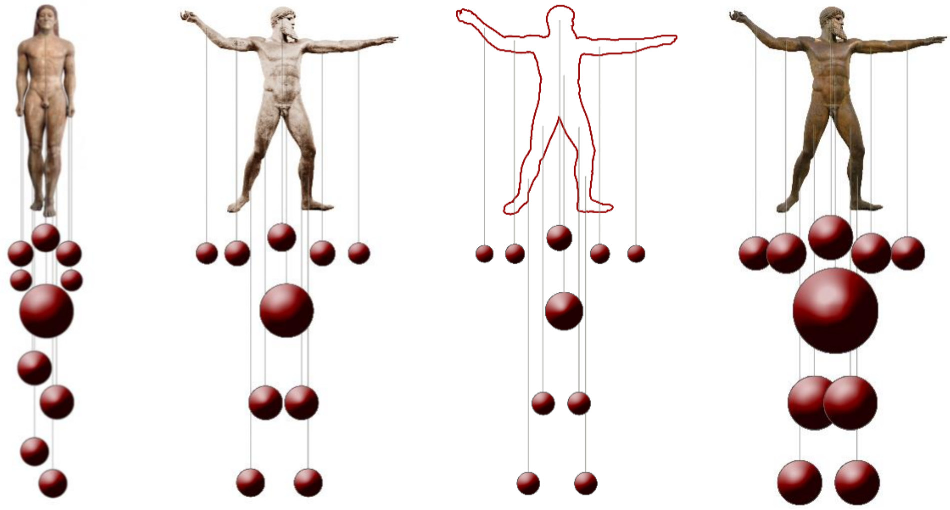


Figure 7. Analysis of forms and forces in Ancient Greek sculpture: (**a**) massive marble, carving method: Kouros c. 530 BC; (**b**) massive marble, simulation of Poseidon of Artemision c. 460 BC; (**c**) lost-wax casting (as created) of Poseidon of Artemision c. 460 BC (section of the statue represents lost-wax casting method); (**d**) massive bronze, Poseidon of Artemision c. 460 BC (statue figures adapted from [27,28]).

Roman sculptors preferred the carving of marble [29], instead of creating bronze sculptures by the lost-wax casting method as it was simpler and probably cheaper. However, lost-wax casting was used in small-scale artifacts [30].

In the Early Medieval Period, when Christianity prevailed, the creation of large sculptures was not encouraged, as sculptures represented a paganist culture; therefore, until the Late Medieval Period, the lost-wax casting method was forgotten.

Sculpture came back during the Renaissance and the lost-wax casting method was recovered possibly by Leonardo Da Vinci (1452–1519) for small-scale statues [31]. The emblematic artwork, which signaled the return of the lost-wax casting method, was "Perseus with the Head of Medusa" (1545–1554), by Benvenuto Cellini (1500–1571), who studied the writings of Pliny the Elder [32–35].

It is important to note that the lost-wax casting method uses the same principles as those used to date (with updated materials: synthetic wax, rubbers, etc.). It is a very complicated method, which requires knowledge of materials, metallurgy, geometry and fluid dynamics; it can also be used as a footprint for understanding each society's technological level. Indicatively, during the Dark Ages in Europe, the lost-wax technique had been forgotten.

2.4. 3D Scanning and 3D Printing

After the lost-wax method, the next step of the evolution of sculpture techniques was the use of synthetic materials in sculpture (e.g., rubbers and resins), which formulated interesting realistic large-scale sculptures [36]. However, the big step was the combination of 3D scanning and 3D printing [37] in the creation process, which provided a new tool for the production of prototypes in multiple scales [38].

Additive manufacturing (AM) is the process of building a physical object using modeling data [39]. An object is digitized (today with 3D scanning) and recomposed by a machine (today with 3D printing). Marquardt and Zheng [40] highlight that the first steps of 3D scanning/printings came from the field of sculpture:

> *The early roots of 3D printing lie in photo-sculpture and topography [41]. In 1860, French artist François Willème patented a photo-sculpturing method. In this process,*

the subject is placed in a circular room and photographed simultaneously by 24 cameras equally spaced around the room. Willème then traced the 24 profiles using a cutter attached to a pantograph. Tracing the profile's shape would simultaneously cut the wood. He assembled these layers of wood to create a photo-sculpture.

The next step in 3D scanning was the integration of digital technology, which began during the 1960s [42], but an increasing trend of "3D scanning" can be found in papers and articles after the 1990s when computers started to become much more powerful (Figures 8 and 9). The first 3D scanning of large statues can be found in the report of "The Digital Michelangelo Project: 3D Scanning of Large Statues" by the University of Stanford, in 2000 [43]. Digital 3D printing started in 1984 [44,45], but the systematic research is more recent and began around 2010 (Figures 8 and 9).

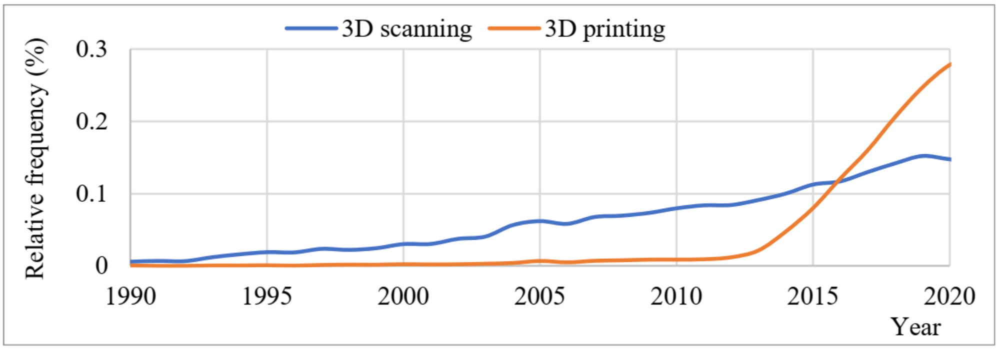


Figure 8. Relative frequency of appearances of the indicated key phrases in the article titles, abstracts and keywords of about 70 million articles written in English, which are contained in the Scopus database [46] up to 2020.

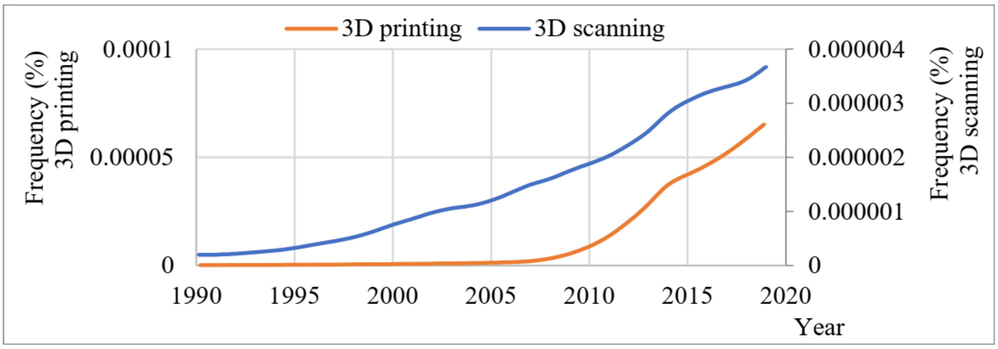
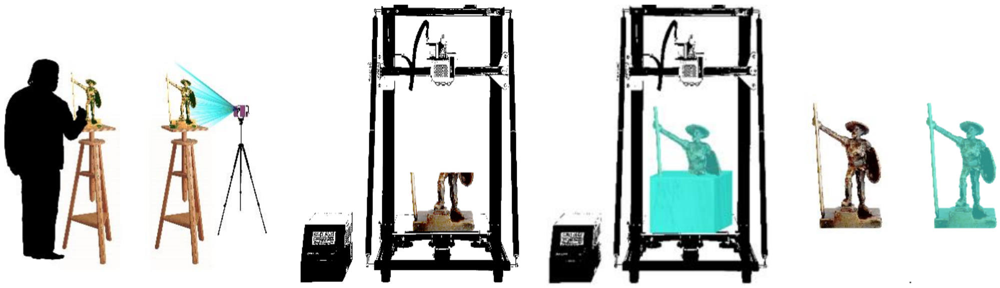


Figure 9. Frequency of appearances of the indicated phrases in Google Books up to 2020 [47]. Data adapted graphically by [48].

With this process, the artist can create the model digitally or naturally. Digital models are sent directly to the 3D printer. Natural models are scanned (Figure 10a,b). The scanning can be performed with a laser scanner or using the principles of photogrammetry. These methods export 3D digital model files, which are compatible with a 3D printer. There are two main methods of 3D printing: adding the material in layers (Figure 10c) or removing the material from a mass (Figure 10d). The artifact can be created with synthetic materials, metals or even marble stones (Figure 10e).



(**a**) (**b**) (**c**) (**d**) (**e**)

Figure 10. Basic steps of 3D scanning/printing: (**a**) creation of physical model; (**b**) 3D scanning; (**c**) 3D printing in layers; (**d**) 3D printing by removing the material from a mass; (**e**) production of the artifact to any scale with marble, metal or synthetic materials.

In recent years, we have witnessed an increasing trend in 3D scanning/printing research. Obviously, the majority of this does not concern sculpture. AM is very often referred to as the new industrial revolution [49–51] and 3D scanning/printing technology is moving into an expanding realm of fields [52], from medical equipment [53–55] to car parts, to houses [56,57].

3D printing has an impact on the manufacturing and distribution of goods; artists and designers are adopting this technique in intriguing ways. As sculpture uses all the available technology in the creation of prototypes, it is strongly related to the ability of the construction. Many researchers and inventors have devoted their time to this evolution. Mongeon [58] quotes Bruce Beasley, who discussed the freedom of creating fine art using a computer:

> *It is like a composer sitting down with notes and chords to get a feel for where the music is going.*

In the same book [58], Mongeon analytically describes the basic knowledge needed; the aspects and capacities of the creation process and digital modeling; 3D scanning techniques; CNC milling and rooting; enlargement techniques; and shows how digital technology could infiltrate the lost-wax casting process. With this book, Mongeon builds bridges between technology and traditional sculpture and motivates traditional sculptors to:

> *Consider the digital process as just another tool that you are trying to master*

In 3D scanning technology, we can distinguish the following processes: photogrammetry; structured light scanning; laser scanning and computerized tomography [59].

- Photogrammetry is a method by which we can create 3D models using many photographs of an object from different angles [60]. The first steps of photogrammetry were made in the field of surveying for the purpose of modeling geographical terrain [61]. The only instruments needed are a camera and appropriate software. The increasing demand for modeling and digitizing the real world in recent years has led to the radical development of the applications of photogrammetry [62–65].
- 3D scanning using structured light is a method by which structured patterns of light are projected onto an object, which distorts it. By analyzing the distortion of structured light with appropriate software, we can create a 3D model from a single picture [66–68].
- 3D scanning using lasers detects the coordinates of the object in space measuring the direct time of flight of laser light beams or using triangulation to detect the distance [69–74].
- Computerized tomography (CT) is a method where a series of 2D X-rays photographs is taken in different sections. Even though this method has been used in the 3D modeling of sculptures for high-value artifacts [75,76], it is very expensive and complex. Most applications of CT scanning are in medicine [77].

However, we note that for the optimization of 3D modeling [78,79], recent research combines more than one method to produce the model, most often photogrammetry along with laser scanning [80–83]. In addition, as many artists are not familiar with new inventions, there are many compact commercial scanners, which apply a multiplicity of processes to extract the optimum results [84,85].

Even though the results are dependent on the quality of the available equipment [86,87], in Table 1, we evaluate the capabilities of each method on the basis of their operating principles.

Table 1. Advantages and disadvantages of different methods of 3D scanning for sculpture.

	Photogrammetry	Structured Light	Laser Scanning	Computerized Tomography
Equipment	Software; powerful processing	Specialized equipment	Specialized equipment	Highly specialized equipment
Users' training	Advanced	Typical	Typical	Highly professional
Indoors/outdoors	Indoors and outdoors	Only indoors	Indoors, errors in bright environment	Only inside the scanner
Large objects	Yes	No	Yes	No
Texture	Good depiction	Good depiction	Errors in metal textures	Excellent depiction
Precision	Needs specialized calibration for high precision	High	High	Excellent
Easy to get results	No	No	Yes	Yes
Cost	Low	Medium	Medium	Very high

Describing the application of 3D printing technology in sculpture, Yu notes [88]:

> *The rise of 3D printing technology makes sculpture completely bid farewell to the manual era and enter the era of digital design and manufacturing. Sculptors design sculpture models by relying on computers, which is conducive to promoting the development and innovation of sculpture art. 3D printing technology can display the pictures depicted in the hearts of artists and sculptors in the form of real objects completely, which can maximize the artistic expression.*

Common processes of 3D printers are CNC routers (CNCR); stereolithography (SLA); selective laser sintering (SLS); fused deposition modeling (FDM); digital light process (DLP); multi-jet fusion (MJF); PolyJet (PJ); direct metal laser sintering (DMLS); electron beam melting (EBM); wire arc additive manufacturing (WAAM).

Three-dimensional printers extract 3D models in cross-sections and create objects in layers. Once a layer is complete, the printer proceeds to create a new layer [89]. We can distinguish different methods from the process of layer creation.

- CNCR is the "old fashioned" 3D printing method with limited printing capabilities. A router guided by the 3D digital model makes cross-sections, subtracting the spare material from a mass [90,91].
- SLA: A laser ray is guided point to point, hitting a polymeric liquid. When the laser hits the liquid, a chemical process is triggered, which solidifies the liquid [92].
- SLS: A leveling roller spreads a thin layer of powdered material across a powder bed. A CO_2 laser traces the cross-section of the material, and as the laser scans the surface, the material is heated and fused together [93].
- FDM: Thermoplastic and support materials are used to create the cross-section of each part. Uncoiled material is slowly extruded through dual heated nozzles. The extrusion nozzles precisely lay down both support and thermoplastic material upon the proceeding layers [94–96].
- DLP: A light projector is used to project the image of an entire layer simultaneously on a polymeric liquid. The layer is created when light hits the liquid [97].
- MJF: An inkjet array is used to selectively apply pixel-like elements of a synthetic material. After its application, material is fused into a solid layer of a specific geometry [98].

- PJ: A print head is used to deposit small pieces of ultraviolet curable material, eventually forming a single cross-section. An ultraviolet light attached to the print head simultaneously cures the material as it is printed [99].
- DMLS has the same principles as SLS, using powdered metal across a powder bed and melting it using a laser [100,101].
- EBM has the same principles as SLS using powdered metal across a powder bed, melting it using a cathode filament [102,103].
- WAAM: A robotic arm with an electric arc welding process is used to melt a metal wire. Guided by the 3D digital model, the robotic arm accurately deposits the melted metal in layers [104,105]. This method is considered to be very promising with a wide range of printing capabilities (large-scale projects) [106].

However, we have to note that new 3D printing methods and improvements of the existing methods are constantly invented [107–113].

Three-dimensional printing products are dependent on the available equipment [114]. Technological steps constantly improve their capabilities. In the following evaluation of methods (Table 2), many of the presented disadvantages could be bypassed by increasing the available time and budget [115].

Table 2. Advantages and disadvantages of different methods of 3D printing in sculpture.

	Synthetic Material						Metals			
	SLA	**SLS**	**FDM**	**DLP**	**MJF**	**PJ**	**DMLS**	**EBM**	**WAAM**	**CNCR**
Details	Excellent	Good	Average	Average	Excellent	Excellent	Excellent	Good	Good	Good
Colours	Limited	Multi	Multi	Limited	Multi	Multi	Metal	Metal	Metal	Material
Texture	Average	Excellent	Average	Rough	Rough	Excellent	Excellent	Good	Good	Rough
Durability	High	Good	Average	Good	High	High	Excellent	Excellent	Excellent	Excellent

The creative capacity of 3D scanning/printing for sculpture is elucidated in related papers. Employing both 3D printing and photogrammetry, Swearingen et al. helped to maximize the value that both designers and artists can add [116]. Using 3D scanning/printing technology to repair a damaged sculpture, Wang et al. used reverse engineering software with wonderful results [117]. Through a dialectical analysis of technology and art in sculpture creation, Du [118] concluded that the art of sculpture should fully integrate, accept and utilize three-dimensional digital modeling technology, instead of treating it with an opposing attitude. We have to note that artists such as Peter Lang [119], Sebastian Errazuriz [120], Arthur Mamou-Mani [121], Stefan Maier and Giacomo Pala [122], Wilhelm Koch [123], Alan Phelan [124] and Joris Laarman [125] have developed impressive creations using 3D printing.

In order to evaluate the effectiveness of 3D printing in traditional materials, we compare the materials used in 3D printing against marble and bronze [126–128]. The loads in a statue are defined only by its own weight; this means that density is critical. In addition, we have to consider that the goal in sculpture is the freedom of the forms; therefore, critical loads of the structure are mostly tensile loads. Figure 11 shows that 3D printing materials are significantly lighter and stronger than marble. Considering metal 3D printing [129], we note that 3D printing adopts the strength of bronze and other more durable metals, such as titanium [52,130,131].

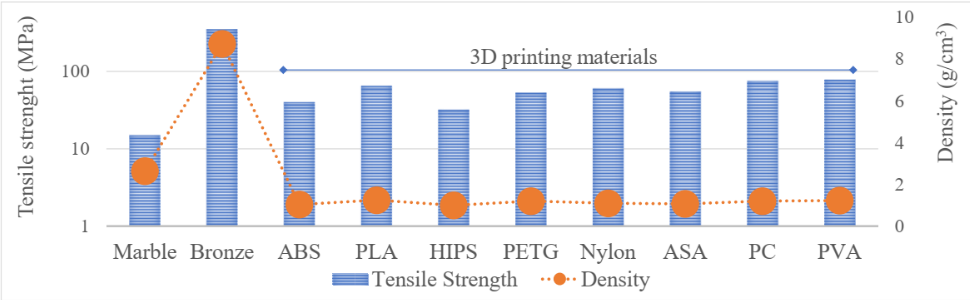


Figure 11. Evaluation of marble, bronze and common 3D printing materials. ABS: acrylonitrile butadiene styrene; PLA: polylactic acid; HIPS: high impact polystyrene; PETG: glycolized polyester; ASA: acrylonitrile styrene acrylate; PC: polycarbonate; PVA: polyvinyl alcohol.

It is also interesting that 3D printing can contribute to previous technological techniques (lost-wax casting) making casting molds for metal by 3D printing.

2.5. 3D Scanning/Printing as a Stride for Civilization

On the one hand, the creation of sculptures is a social expression, which uses all the available knowledge and the technology of each era; on the other hand, it offers durable art works, which can be used as a reliable footprint for civilization.

Sculpture techniques began with the carving method in prehistory until the era of Classical Greece, where it changed to the lost-wax casting method, which helped the expression of artists and mainly liberated the depiction of statue movement. During the Dark Ages, the lost-wax casting method was forgotten, and medieval statues were created using the carving method. In Renaissance, Da Vinci and Cellini recovered the lost-wax casting method, which used the same principles until now. Three-dimensional printing is the only new technique for making sculptures since Classical Greece and is a very important innovation of our days (Figure 12).

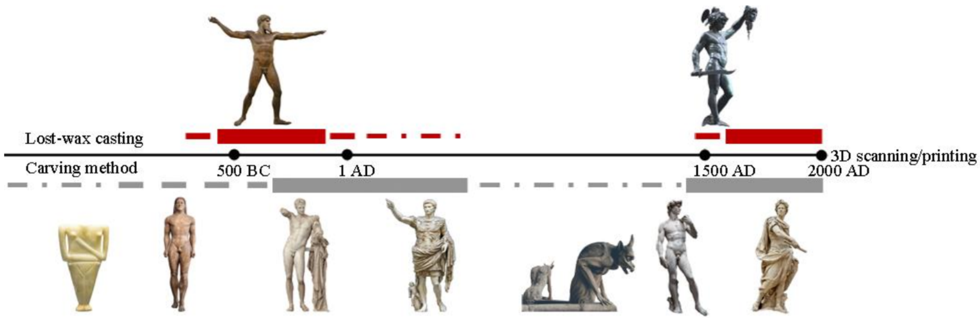


Figure 12. Timeline of sculpture techniques. In grey is a qualitative evaluation of the presence of carving method, and in red is a qualitative evaluation of the presence of lost-wax casting.

3. Material Poetics in 3D Scanning/Printing

When we perceive art, we process it logically and emotionally, a process expressed in the phrase "this is beautiful". This is the claim in the foundation of aesthetics, and there lies the difficulty of the matter. Today, the claim of logic is that "a $\equiv$ a", and this is rather certain. The criteria, however, for what is beautiful constantly change and are not universal. Above all, every creation belongs to a specific cultural tradition. What is beautiful for somebody is not necessarily the same for someone else. Everyone would agree that Picasso was a genius, but none would have known him if some museums and groups did not choose to elevate Picasso's artworks [132].

This is why people think of words such as "art", "aesthetics" and "beauty" as something temporal. However, we try to find general rules to adapt them [133–143] as the depiction of beauty in an era is an important factor that helps us imagine its cultural characteristics.

Studying art objects, forms and materials, we can inspect the processes through sculpture, such as their lifespan, and many other aspects, but a basic question arises: where can we find the material poetics?

In general, we could say that poetics is the creative process where the full potential of the raw material is utilized for the realization of the desired result. In this very wide meaning, the term is used mainly metaphorically to describe the extent to which the material and the technique are used in such perfect harmony that the artifact exceeds its useful purpose and acquires the quality of a kind of "poetry", an achievement in itself. It is relevant to note that the origin of the world "poetry" is the Greek "ποίησις", which is etymologized from the verb "ποιέω", meaning to make, produce or create in Ancient Greek.

The approach of studying material poetics concerns the artist's soul. This approach is connected to the process of creation and the interaction of the material with the intention of the artist. Thus the observer feels that he has a unique view of artist's soul. In the art market, a unique artifact made by the hands of an artist is more valuable than an artifact made in multiple copies. Recent studies introduce methods of copyright protection in 3D digitized artistic sculptures by adding unique local inconspicuous errors by sculptors [144].

It is noted that 3D printing introduces an additional stage (3D manufacturing) between the artist and the observer which gives also the ability of unlimited copies. This kind of production is performed using various synthetic materials which create a distance between the artist and the artifact; thus, sculptures lose the concept of material poetics. However, metal printing methods, such as DMLS, EBM and WAAM, circumvent these issues.

4. The Role of 3D Scanning/Printing in the Preservation of Culture

We could say that the main characteristic of sculpture compared to other arts is its ability to endure the effects of time. However, during Medieval Times, many artworks of antiquity were destroyed due to cultural and social changes. Poetry and writing manuscripts were easily lost and were often saved in fragments. Music disappears with each culture even in the era of printing (where many musical scores have been lost or their composers are unknown). Paintings are created in one plane, and the aging of materials will inevitably alter their presence [145]. On the contrary, many sculptures of antiquity have passed through the Dark Ages and came to present with few deteriorations, showing a remarkable ability to endure the effects of time.

Statues in public places symbolize historical moments as they are large-scale projects [146] and vehicles carrying historical memories. They are considered as objects bearing the spirit of the place (Latin: *genius loci*) [147], and as an important mark of the civilization [148]. In times of social unrest, a typical reaction is the demolition of sculptures. However, even if something is unpopular in a specific historical moment, it is a disaster to lose any piece of a society's cultural heritage as it deprives the next generations of the ability to study it.

Many times, in history, we have seen the demolition of sculptures due to changes in the social paradigm. For example, statues depicting pagan gods demolished by Christians in antiquity (Figure 13a), but also in modern times: statues of Lenin and Stalin demolished during the perestroika (Figure 13b), Saddam Hussein's statue after the invasion of Iraq in 2003 (Figure 13c) and statues of American explorers during the "Black Lives Matter" demonstrations of 2020 (Figure 13d).

(**a**) (**b**) (**c**) (**d**)

Figure 13. (**a**) Aphrodite' 1st century AD. Christians grave a cross on chin in order to exorcize the paganism features of the statue [149]; (**b**) demolition of Vladimir Lenin statue (2013) [150]; (**c**) the toppling of Saddam Hussein's statue (2003) [151]; (**d**) Christopher Columbus' statue after it was pulled from its pedestal by American Indian Movement protesters (2020) [152].

It is noted that statues can be harmed by collateral damage from violent acts. Biris writes that around c.1850 [153], the King of Two Sicilies gifted three exact copies of Hercules of Farnese, Flora of Farnese and Nike of Samothrace made of plaster to the National Technical University of Athens. Unfortunately, during the 20th century, as Greece went through various troubled times, the National Technical University of Athens, which is protected by academic asylum, became the epicenter of many explosion events, a fact that changed its status to a landmark for sociopolitical conflicts. This caused a large amount of damage to the infrastructures of the university (Figure 14a).

We do not know the exact date of the demolition of these sculptures, but in the late 1990s, these sculptures were broken, and their pieces were kept in storage (Figure 14b). Furthermore, a big research project had to be done in order to restore them (Figure 14c) [154].

(**a**) (**b**) (**c**)

Figure 14. (**a**) Burning of the historical rectory (24–25 October 1991) (image snippet from [155]); (**b**) part of the statue Hercules of Farnese during restoration (2003) [25]; (**c**) restored copy of the statue Hercules of Farnese (2005) [25].

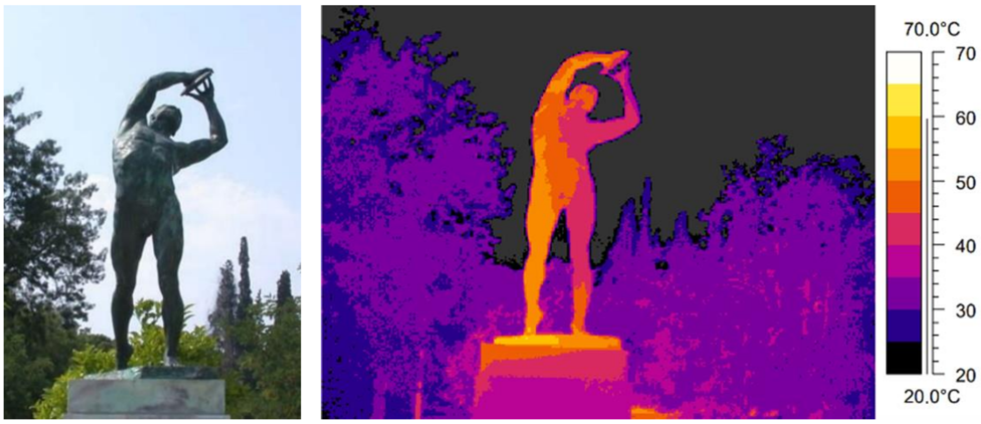
Other types of accidental damage during art creation could also be catastrophic for the molds or for the artworks themselves.

Figure 15a shows the destroyed sculpture studio of G.-Fivos Sargentis [156] after an explosion. A fire destroyed the place and uncountable molds and statues on 15 June 2021. Prototypes made of natural wax were completely destroyed (Figure 15b,c).

(a) (b) (c)

Figure 15. (**a**) Sculpture laboratory after the fire of 15 July 2021; (**b**,**c**) anaglyph of Saint Procopius made by natural wax, which was lost in the fire.

Destructive accidents could also occur during the exhibition and transportation of artwork. In addition, attempts at restoration have also damaged artworks, even by experts who used techniques that were unsuitable or harmful, as found later. In addition to laboratory accidents, another important factor for sculpture degradation is the natural aging of the materials in outdoor environments. Important aging factors are corrosion [157–162] and temperature fluctuation as contraction–expansion causes fatigue forces in statues (Figure 16) [25].



(a) (b)

Figure 16. (**a**) The Discobole (Discus Thrower) in Athens. Date of creation: 1924. Sculptor Constantinos Dimitriadis (1881–1943). (**b**) Infrared image of Discobole, Athens 4 July 2003, 15:00 [25].

Three-dimensional scanning and 3D printing provide important opportunities [163–165] to conserve cultural heritage as we can keep them in computer files or in a small scale [166]. Hosting small prototype models (small-scale sculptures) of urban statues of Saint Petersburg, in the State Museum of Urban Sculpture (Государственный музей городской скульптуры) [167], one can see prototype models of communist monuments that were demolished in the past.

Lately, portable 3D scanning is easily accessible [168] (even with mobile apps from smartphones [169]). In this way, 3D files of cultural heritage can be backed up and archived for future sharing [170–173]. Items that are too fragile for display can be stored safely, while a replica takes their place; additionally, items can be touched and their shape can be explored through a printed artifact [174]. This is a way for children or disabled people to have a close connection with heritage objects [175,176].

In addition, considering that technology changes very fast, and sometimes it is difficult to read digital files created only 30 years ago, e.g., stored in floppy disk, 3D printing is a safe method for storing and preserving our cultural heritage [177,178].

5. Conclusions

We have seen that sculpture produces objects of art often associated with the public space, carrying high public significance. Even if the artistic value of many sculptures is questionable, we have to note that sculptures are products of a culture in a given historical period that follow the collective technological progress of the society in question. Figures 6 and 7 show the results of adding creative capacities during the transition from carving to lost-wax casting, which liberated artists to design free forms.

The first steps of AM were carried out in 1860 by the French artist François Willème, who patented a photo-sculpturing method. The digital innovations of recent decades are a stride in the history of sculpture and leave their own footprint on civilization (Figures 8 and 9). Three-dimensional scanning/printing is the first widely spread innovative technique for the creation of sculptures after lost-wax casting, which was introduced in Ancient Greece (Figure 12). Different methods of 3D scanning/printing are evaluated in Tables 1 and 2. The summary of the results is presented in Figure 11, showing the advantages of 3D scanning/printing.

Three-dimensional printing offers new potential, and its multiple applications enables new possibilities in art and technology; these aspects can be observed by studying the evolution of sculpture techniques. Figure 12 shows the importance of this technological step in sculpture history, which also signifies the capacity for making prototypes. In addition, 3D scanning/printing helps to preserve our cultural heritage, although the material poetics are lost, as additive manufacturing offers the rapid construction of prototypes with different standards.

The issue we have to consider in the field of sculpture for further research is how this 3D scanning/printing could overcome the problem of material poetics being lost in this process. Further research could study the relation between carving/lost-wax casting and 3D scanning/printing in equivalence to the relation between painting and photography.

These first steps for 3D scanning/printing represent merely a small component of its possible uses and future fields of implementation, which seem to be very promising.

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