Chapter

3D Printing and the Art World: Current Developments and Future Perspectives

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Abstract

3D printing's rapid technological development is starting to impact the art field because, for the first time, it has become possible to exactly reproduce and reconstruct artworks without any loss of their physical features. Yet, a coherent overview of how 3D printing is used within the art field while paying attention to ethical considerations does not exist. This study will provide an overview of the current developments of 3D printing in the art world, its use, and the direction it is moving toward. Within this study, the technologies that enable, influence, and will continue to affect the 3D reproduction of artworks, namely technologies necessary to capture an artwork's materials on a chemical and physical level, artificial intelligence (AI), 3D printing technology itself, and the rise of the non-fungible token (NFT) are analyzed to be able to understand what 3D printing implies for our changing perception of art in the future.

Keywords: 3D printing, art, cultural heritage, authenticity, 3D scanning

1. Introduction

In 2011 CE, the British paper *The Economist* announced that 3D printing would change the world:

> *"Three-dimensional printing makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. [...] Just as nobody could have predicted the impact of the steam engine in 1750 CE — or the printing press in 1450 CE, or the transistor in 1950 CE — it is impossible to foresee the long-term impact of 3D printing. But the technology is coming, and it is likely to disrupt every field it touches." [1]*

Nowadays, it is possible to mass produce a large variety of objects in different materials, complexities, shapes, and sizes: from boat propellers to nanochips as small as a 1μm; from pizzas to pills, prosthetics and organs; and from firearms to entire glass houses. As *The Economist* rightly predicted, it would be a matter of time before 3D printing would enter the art world. In contrast to other reproduction techniques (e.g., photography, augmented reality (AR), virtual reality (VR), handmade), 3D printing not only replicates the whole three-dimensional object including its color but also offers the ability to vary the texture of surfaces, translucency, and glossiness. Moreover, due to the digital nature of this technology, it becomes easy to manipulate and alter these material elements, making it possible to endlessly reproduce a diversity of versions of one single artwork [2]. These factors also immediately appeal to contemporary artists to use this fascinating technique as a new medium for artistic expression and cultural reinterpretation, for example, American artist Mark Dion's *Waiting for the Extraordinary* (2013 CE), *The Natural Sciences* (2015 CE), and *Leiden University Phantom Cabinet* (2017 CE). In this work, he used 3D printing to replicate specimens from early scientific collections of Museum de Lakenhal, Natural History Museum Naturalis, and Leiden University (e.g., a saw of a sawfish, a microscope, and a sword) and covered them with glow-in-the-dark paint (**Figure 1**). Furthermore, by combining 3D printing with digital imaging techniques almost indistinguishable copies of oil-painted paintings can be created. Moreover, 3D prints can be made of materials that are more resistant to environmental conditions (like variations in humidity, exposure to (day)light and temperature fluctuations) than traditional materials found in artworks, making them possibly more durable and far less fragile than the original, thus adding to the longevity of artifacts. Moreover, artificial intelligence (AI) and the way it can use digital art historical and material information to be able to alter, predict, and shed new light on the material state of an artwork and an artist's creative process is rapidly developing. Combining AI with 3D printing will undeniably have its effects on the art field and our perception of art history.

This chapter aims to shed light on the way 3D printing currently impacts the art field and the role it will have in the future. Firstly, it will be discussed which ethical considerations to keep in mind when reproducing cultural heritage (CH) objects and artworks. Based on the latter, an overview will be provided of how the technology is

Figure 1.
Mark Dion, Leiden University Phantom Cabinet, 2017 CE, detail, wood, polyamide, fluorescent paint, 2 × 3 × 3 m. Image by author.

currently being used within the art field. Furthermore, the current status and developments within the technologies that enable, influence, and will continue to affect the 3D reproduction of art will be discussed. These enablers are the technologies necessary to capture an artwork's materials, AI, and 3D printing technology itself. This chapter ends by showing what is on the horizon and what the continuous development of these technologies potentially signifies for our perception of art in the future.

2. Art and authenticity

When considering the reproduction of art, one aspect that automatically comes to mind is the authenticity granted to artworks. Authenticity is a complex and heavily debated concept and continues to be of importance, especially with the introduction of high-quality reproduction methods such as AR, VR, and 3D printing. Describing the term authenticity is challenging as it is diverse, culturally determined, and personal [3]. In the case of Western culture (the context in which this chapter is written), Walter Benjamin's essay (1936 CE) on "mechanical reproduction"—in his time photography—has laid the foundation for the current way of thinking about the connection between reproductions and original works of art [4]. He described that this type of reproduction makes it possible to capture reality instantly at a high quality, facilitating the infinite display of artworks at any place and at any time. Consequently, the exclusivity of art and heritage disappears, because the mechanical reproductions—3D printing in our case—extracts the artwork from its tradition and meaning in history because it can be anywhere at any time. This way, art loses its authentic experience or "aura," which is encapsulated in its unique materials. This way, "authenticity," can still be linked to the quality of being authentic, unique, or genuine. This aspect is automatically linked to the material of the original artwork as the only true element that forges a connection between the past and the now, with the beholder and the artist.

Although we have become more used to seeing artworks everywhere through facsimiles, this has not led to a decreasing interest in the original. The popularity of museums, where the original is highlighted, and the importance of conservation and restoration to keep an artwork's materials intact show that this has been increasing. Seeing the massive crowds in front of Leonardo da Vinci's *Mona Lisa* (1503 CE), it could be argued that art's popularity has resulted in the objectification of authenticity and a greater emphasis on the artwork's uniqueness, rejecting almost any form of (physical) reproduction. With this definition of authenticity, 3D printing art and CH objects cause a complex discussion. Namely, a 3D print can never comply with originality in materials and could thus be labeled as "anti-authentic."

However, there are an increasing number of studies that show a shift in the way authenticity can be granted [5–7]. In an increasingly connected world through digitalization and technological advancements, it would be short-sighted to consider authenticity as something singular, static, and based on tangible and physical aspects alone. Furthermore, the ephemeral character of contemporary artworks indicates that art and CH's value are also dependent on intangible and more conceptual qualities. For instance, emotional and/or religious connections to an artwork, its significance in a cultural context, the idea of the artist, or the functional qualities of the object. Thus, only a small part of the notion of authenticity depends on the artwork as a material expression of a fixed moment in time and space. Rather, "aura" should be seen as a network, an interplay between the physical historical artifact and its intangible and emotional and social values which is ever-changing.

In this way, 3D printing artworks could be considered useful for the CH field. Indeed, there are a growing number of studies on the perception of 3D-printed facsimiles confirming the significance of this technology in creating sustainable and durable bonds between the beholder and the object [8]. Although the interest in the authenticity of art and the unique object has not diminished, yet, because only one true material version of the artwork exists and should be conserved for as long as possible, a 3D print could be acceptable as long as it enhances the authentic value of the artwork and does not pretend to be the original. What this means is that when considering the use of an ethical 3D print, it should display or do something the original artwork cannot do due to its fragile materials. For instance, the 3D print can make it possible to display an artwork which is otherwise too fragile to travel; show an artwork without discolorations and closer to what it must have looked like when it left the artist's studio; present an object in its original setting instead of in a carefully conditioned museum; or provide the possibility to touch the artwork or artifact. With this in mind, through a 3D print, new experiences and narratives can take place both inside and outside the museum, with the indication of course that it is a copy and why it is there. Important to always keep in mind, however, is the fact that reproductions both extend an artwork's history and connection with the public but, at the same time, freeze the artwork's image and might imprint a specific significance for generations to come. Therefore, consider what the 3D print communicates and why as it might impact the perception of the artwork in the future. Of course, a 3D print will and can never replace the original, but it allows us to think about the value of the artwork and the range of new connections between visitors and artwork, making the original even more important. In this way, a 3D print could provide a best-of-both-worlds scenario. By eliminating the need to make compromises as every material aspect of the artwork can be reproduced, 3D printing is important to the desire to keep in touch with the physical. At the same time, it can fulfill the need for a more multifaceted story of one artwork sustainably and durably [5–9].

3. Current applications

Currently, 3D printing products are highly accurate and precise and can be made with a wide variety of durable and inexpensive materials. Furthermore, in comparison with traditional processes of creating physical reproductions, 3D printing is highly flexible: The relative ease with which digital data can be modeled, scaled, modified, and used has made the technology irresistible for the cultural heritage field [10]. Moreover, as Moritz Neumüller (Ph.D. in New Media) says: "3D Printing will not only become vital in the field of reconstruction of objects, but also for research, documentation, preservation and educational purposes, and it has the potential to serve these purposes in an accessible and all-inclusive way." [11]. This rapid diffusion of 3D printing has already had its effects in the field of cultural heritage and fine art museums as there are various reasons for creating reproductions. The overview will be divided as follows:

- Restoration and reconstruction
- Documentation and accessibility
- Research and education
- Museum presentation and interaction

3.1 Restoration and reconstruction

As various studies on the application of 3D technologies for conservation show, 3D printing is considered useful for the conservation, restoration, and preservation of artworks and CH [11, 12]. Yet, in the case of more 2D art forms such as painting, the application of 3D printing is more challenging due to the complexity and large range of the different materials used to create one single artwork [13]. Therefore, the exploration of 3D printing has mainly been applied in archaeology, architecture, and sculpture for the conservation, restoration, and preservation of damaged and fragmented or objects that do not exist anymore. An exemplary case is the restoration of French impressionist Auguste Rodin's (1840–1917 CE) sculpture *The Thinker* (1881 CE). In 2007 CE, the statue was heavily vandalized in the museum, and Singer Laren (The Netherlands) was burglarized [14]. In this case, scanning the still existing original mold of the sculpture that was located at the Rodin Museum in Paris made it possible to create positives of the missing elements. This was used to create a cast (a negative) to fabricate corresponding facsimiles of the sections of the statue that were missing, such as parts of its leg and face. Similarly and one of the rare instances, when 3D printing is used to restore a painting, is Vincent van Gogh's *Zeezicht bij Scheveningen* (1881–1883 CE) in 2019 CE [15]. Here, 3D printing was combined with photographs of the artwork before it was damaged to reconstruct a mold for the piece of paint that was missing. In both instances, 3D printing was used to recreate missing parts using similar materials to the original artwork. Additionally, there are multiple examples where 3D-printed copies were directly attached to the original artwork's materials. A 3D print's compatibility and long-term stability make it an interesting method as there is no intention to replace the parts frequently. An often referred to example is the restoration of the fingers of one of the figurines on the tomb in the chapel of Villa Borromeo d'Adda in Arcore (Italy) [16]. Based on a 3D scan of the broken hand which was combined with a drawing of the complete statue when its fingers were not missing, the restorers were able to reconstruct and eventually 3D print the missing parts. The 3D-printed parts were painted in the colors of the marble and attached to the statue using magnets, thus resulting in a non-invasive (and reversible) restoration treatment.[1]

However, 3D printing has not only proven to be a useful technique for saving artworks that are partially incomplete, fragmented, or damaged. *The 3D reconstruction of Nineveh* is an interesting example to show that 3D printing is a welcome method to reconstruct artifacts or archaeological sites that have been lost entirely. Here, black-and-white photographs made by archaeologists were used to reconstruct the texture of the Bas-reliefs of the Southwest Palace of Sennacherib (700 BCE) in Nineveh (Iraq) [18]. This photographic information was translated into 3D printable data to recreate the reliefs that were destroyed by the Islamic State. Furthermore, the reproduction of existing artworks may help restore the original context they were displayed in. For example, renaissance painter Paolo Veronese's (1528–1588 CE) *Wedding at Cana* (1562–1563 CE) in Fondazione Giorgio Cini (Venice)—of which the original hangs on opposite Leonardo da Vinci's (1452–1519 CE) *Mona Lisa* (1503 CE) in the Louvre (Paris)—restored the original context the artwork was made for [10, 19].

[1] To read more about similar projects executed by Mattia Mercante in collaboration with FormLabs see: [17].

3.2 Documentation and accessibility

Not only did the previous examples show that 3D printing can be used to physically reconstruct parts or entire artworks for restoration purposes, but it also shows that 3D printing can document lost artifacts and make them accessible once again. This is exemplified by the Spanish company Factum Foundation which used 3D printing to reproduce the Egyptian pharaoh Tutankhamun (2009) and pharaoh Seti's (2016) tombs located in Egypt's Valley of the Kings in their entirety, including all the details of the tombs' hieroglyph walls (**Figure 2**).[2] Not only did 3D scanning and 3D printing facilitate in making these tombs visible and tangible again without the (further) destruction of the original site, but it also documented the current state of the artifact's materials both digitally and physically [12].

Yet, large-scale documentation of artifacts utilizing 3D printing is not solely limited to accurately measuring, documenting, and sharing the current state of precious artifacts [12]. For example, as the Mauritshuis' (The Hague) exhibition *Rembrandt? The Case of Saul and David* (2015 CE) showed, 3D printing attributed to the reconstruction of the original composition of Rembrandt's *Saul & David* (1660 CE), a painting that was sawn into pieces in the nineteenth century and later reassembled [21]. This example shows 3D printing's possibility of creating tangible representations of the current and past features of an artwork or artifact without damaging the current physical state of the original object [5].

Figure 2.
Facsimile and physical reconstruction of the "Hall of Beauties" for the exhibition Scanning Seti I: the Regeneration of a Pharaonic Tomb (Antikenmuseum, Basel, 2017–2018 CE). Photo credits: Oak Taylor-Smith for Factum Foundation [20].

[2] In this case, Factum Foundation used 3D printing to create a negative with an acrylic gesso. Subsequently, they adhere a highly detailed 2D colored skin to this negative in order to create a high-definition facsimile.

In addition, 3D printing's digitization and the possibility to reproduce these CH objects in various ways are automatically of great benefit for engagement with a larger audience and for facilitating public programming. For example, the Smithsonian Institution (Washington D.C.), The National Museum of Antiquities (Leiden), and the Uffizi Gallery (Florence) digitized parts of their collections in 3D and present these models on open-access forums (e.g., Sketchfab) or their own websites [22–24]. This way, their collections become accessible to people at home, in museums, or in schools who can use these data to 3D print their artworks.

3.3 Research and education

The digitization and the physical documentation and preservation of historical objects and artworks and their consequent accessibility are undeniably beneficial for research on and about these objects as well as an aid for cultural education. In the case of conservation and restoration, 3D printing can be considered useful in assisting the monitoring of an artifact's past, current, and future state, thus making it possible to research the artwork's material behavior [14]. The 3D prints at the Mauritshuis' *Facelifts & Makeovers exhibition* (2022 CE) effectively demonstrated a work of art's metamorphosis due to restoration treatments [25]. The fact that one-to-one reproductions of fragile artworks and artifacts can be made in large quantities makes it possible to study these objects more extensively and, more importantly, in a different way [12]. For example, for the *Scanning for Syria* project (2015–2018 CE), the fragile Syrian clay tablets were 3D printed to aid researchers all over the world in researching what was written on them. Instead of having to physically travel to an object, 3D printing facilitates the accessibility of these objects for a larger group of researchers, making it easier for various researchers to research the same object at the same time. Furthermore, 3D printing's materials and the use of a digital model as a starting point allow the researcher to interact with and handle the cultural heritage objects freely and differently, thus stimulating different kinds of approaches and ways of analyzing them (e.g., through magnification or rearrangement). For example, 3D printing was used as a practical method to better understand and scrutinize the physical qualities of a few Palaeolithic limestone slabs [13]. 3D printing the heads of the figurines of *Laocoon and his sons* (1540 CE) separately and at a larger scale, for the first time, it became possible to study their expressions, which are otherwise inaccessible due to the height of the statue (**Figure 3**). This way, 3D printing facilitates getting a better sense of the object's dynamics, shape, materials, and composition in space [8, 13].

Consequently, this can be beneficial in communicating these findings by using these objects as a means of education. In the case of education, a project initiated by Cornell University in 2008 CE is exemplary, in which 3D printing was used to enable students to access and manipulate the archive of their archaeological collection [11, 13]. It was shown that the use of three-dimensional and physical models was more helpful to the education of children and students than traditional methods [26]. Some museums, such as the Metropolitan Museum of Art (New York) and The Victoria & Albert Museum (London), have been experimenting with this technology as a method to communicate with and educate their users (ranging from visitors to researchers) within and outside of the museum's walls [27]. As a few studies show, 3D printing's use effectively stimulated the creative process of users and this could potentially increase the ease with which cultural heritage objects around us are understood [28]. For instance, the *La Riscoperta di un Capolavoro* (2020–2021 CE) exhibition at Palazzo Fava, Bologna, showed that only printing the surface makes

Figure 3.
3D print of Laocoon and his sons and 3D-printed heads.

it possible to understand the techniques used by artists to create relief and depth without the distraction of color [29]. Thus, 3D prints can potentially stimulate new ways of interacting with and studying art objects, therefore facilitating the possibility to learn from them in a non-invasive way.

3.4 Museum presentation and interaction

In the case of museum presentations, 3D printing has been implemented in various ways already [9]. One way is presenting a 3D-printed model next to the original artwork. In this sense, a 3D print can fulfill something the original material does not allow, such as the possibility to touch the object or show additional information [11]. Furthermore, they can enhance interaction within the museum. An example of this is the Museum Boijmans van Beuningen's (Rotterdam) *Sgrafitto in 3D exhibition* (2009 CE) [30]. Here, 3D-printed reproductions of ceramic plates were placed in front of the original artifacts, allowing the visitors to experience the weight, dimension, and topography of the object in front of them and thus interact with the artwork indirectly. Furthermore, as 3D printing provides a way of handling an artwork without having to use (thus damage) its materials while being easily adjustable as it is based on a digital model—it might be an interesting technology to make art more accessible for people who cannot rely on sight only [10, 12, 31]. *Hoy toca el Prado* (Touch the Prado today) exhibition was hosted in Madrid in 2015 and

2021 CE permanently installed *Feeling van Gogh* exhibition at the van Gogh museum (Amsterdam) used 3D prints of paintings to let the visitor explore their collection through touch.[3] By enhancing a portrait's contours, 3D printing can be used to make the paintings more accessible to visually impaired visitors [32]. Simultaneously, the fact that artworks can be touched could make the experience of art in the museum not only more interesting for children and students, but also possibly more effective [8–10]. Furthermore, 3D-printed facsimiles can replace an original when it is absent because it cannot travel or because it is not available. For instance, a 3D print of *The Anatomy Lesson of Dr. Deijman* (1723 CE) painted by Rembrandt van Rijn (1606–1669 CE) (collection Amsterdam Museum, Amsterdam) was displayed during Fondazione Prada's *Human Brains* exhibition at the 59th Venice Biennale in 2022. Since the gallery does not own a permanent collection, they also displayed a 3D-printed copy of Hieronymus Bosch' The Extraction of the Stone of Madness (1501–1505 CE) (collection El Museo del Prado, Madrid) and many other copies

Figure 4.
3D print of Rembrandt van Rijn, The Anatomy Lesson of Dr. Deijman, 1656, oil on canvas, 100 × 134 cm, Amsterdam Museum, Amsterdam—Photo by author, 3D print by Factum Foundation.

[3] Touching the Prado (Hoy toca el Prado) in El Museo del Prado in Madrid is an ongoing exhibition that exhibits 3D facsimiles of various paintings in the collection and invited the visitor to touch the works of art. The exhibition was first held on January 20th, 2015. Feeling van Gogh in the Van Gogh Museum is "an interactive programme developed especially for blind and partially sighted visitors and their sighted friends, families and carers." The exhibition has been part of the museum since 2021.

Figure 5.
3D print of Hieronymus Bosch, The Extraction of the Stone of Madness, 1501–1505, oil on oak panel, 48.5 × 34.5 cm. Museo del Prado, Madrid—Photo by author, 3D print by Factum Foundation.

as a way of durable and sustainable exhibition building (**Figures 4** and **5**). In this regard, the curators argued that to them, the story of the exhibition is more important than showing original works of art. This, subsequently, can open up a way for museums to rethink the repatriation or decolonization of artifacts to their communities of origin for museums can become less attached to the originals. The *Tlingit* prints in the Smithsonian, (Washington D.C.) are a great example of how creating high-quality 3D prints helped rethink the role of objects and the museum in different societies [33].

As this brief exploration of the use of 3D printing within the cultural heritage field shows, 3D printing is starting to be implemented and its applications are being explored. Furthermore, whereas the technology's potential for architecture, three-dimensional objects, and artworks such as sculptures is developing rapidly and is being researched widely, the 3D reproduction of paintings has not received the same amount of attention. A reason for this could be the fact that the technologies needed to scan and 3D print paintings were not available or developed enough until 2015 CE. Furthermore, the developments of 3D printing and other types of (digital) technologies will undeniably increase the use of 3D printing within the field. The following section will analyze the technologies that enable the 3D reproduction of CH objects by elaborating on the current status and developments of 3D scanning, and the involvement of AI and 3D printing technologies.

4. Capturing and digitizing artwork

To reproduce artworks, they must be digitally captured. Artworks are appreciated because of many aspects, yet their aesthetic qualities are considered to be one of the (if not the) most important features. To be able to scan artworks that all have their unique dimensions, materials, and complexities, the following methods can be considered the most relevant within the cultural heritage field [34]:

- Photogrammetry
- 3D scanning using structured light
- 3D laser scanning
- Computed tomography (CT)

4.1 Photogrammetry

Photogrammetry is a photographic method that measures data about an object by analyzing the changes in position between several pictures taken from various places and angles (with a minimum of two) [35]. After the images are taken, the pictures are aligned and data points plotted, the distance and location of each point in the 3D space can be calculated. Nowadays, this technology is often used within the cultural heritage field because it is rather easy to use and set up as it only requires taking high-quality (high pixels) digital photographs of an object to digitize it into a 3D model.

Although this technology is very useful for capturing (large) three-dimensional objects, it is not as useful in the case of surfaces that are flatter, and uniform without a distinct appearance (e.g., paintings) as it is hard to create multiple angles. For this reason, it is difficult to triangulate the small topographical irregularities, such as craquelure patterns, which can be found on painted surfaces. Furthermore, capturing highly reflective surfaces can be difficult. Another downside of this method is the fact that the optimization of the camera's position relative to the object is not calibrated, making this method oftentimes less accurate than other 3D methods. Moreover, the quality of the 3D model greatly depends on the underlying algorithm and assumptions or optimization used.

4.2 3D scanning using structured light

3D scanning through structured light uses the photography of a single point of a (flat) surface from different angles. This way of 3D scanning uses the projection of a geometric pattern onto the artwork—usually a painting—of choice [35]. By photographing the irregularities and deformations in the projected pattern from multiple angles, it is possible to generate the 3D data of the object. This way, this scanning method is capable of capturing smaller topographic features such as crack patterns. By using a fringe pattern, the data gathered are more precise than the 3D information provided by photogrammetry. With the addition of a polarization camera that takes images both with and without the reflection of the surface, a painting's glossiness can be captured simultaneously [36, 37]. This topography, color and gloss information can be translated into 3D printable data.

Yet, like photogrammetry, this method is less suitable for capturing highly reflective surfaces. Furthermore, because it is a photographic method, it can only record where light can be reflected, making it hard if not impossible to obtain accurate information on deeper sections.

4.3 3D laser scanning

Moving away from photographic methods, laser scanning uses either a static or moving platform that controls the deflection of visible and invisible laser beams. The laser source casts sequences of laser lines onto the surface [35]. These light waves bounce off the surface of the 3D object and are reflected to the sensor. Subsequently, the scanner can determine the three-dimensionality in two ways. The first method is called the time-of-flight (ToF) method, in which the amount of time it took the light beam to go back and forth is calculated. The second method is called triangulation. Here, the known distance between the laser and the camera together with the known angle at which the camera was placed is used to calculate the exact distance between the laser and the object millions of times [38]. Subsequently, when all of these points are processed and mapped together, it becomes possible to form a digital representation of the scanned area. An advantage of this method as opposed to the beforementioned photographic methods is that the light beams can scan through the surface. Therefore, even objects, structures, and areas invisible to the naked eye can be captured and measured with high accuracy (**Figure 6**). However, the laser beams do not detect color or glossiness simultaneously and thus will have to be captured and processed individually. This can lead to difficulties and inaccuracies when integrating the color data with the 3D data, making this technology's use limited and rather exclusive [39].

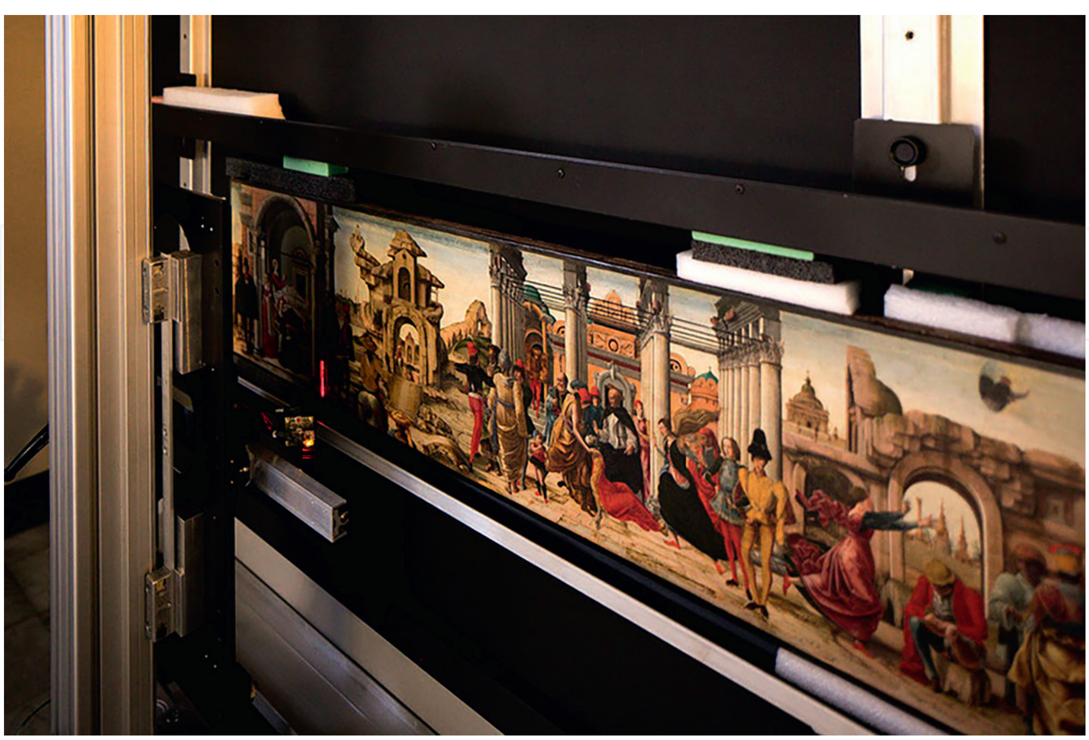

Figure 6.
Recording the surface relief of Ercole De'Roberti's Stories of Saint Vincent Ferrer, predella of the Politico Griffoni, at the Pinacoteca Vaticana. Photo credits: Grégoire Dupond for Factum Foundation.

4.4 Computed tomography (CT)

Computed tomography, which is mostly known for its purposes in medicine, uses X-rays to take a series of radiographs from different angles. By combining these individual 2D images into a 3D image using reconstruction algorithms, it becomes possible to get high-resolution information on the three-dimensionality of an object both internally and externally [40]. This makes the technology costly and not suitable for larger objects. Furthermore, the data are usually presented as a stack of 2D slices that are layered on top of each other. Therefore, because it takes an extra step to create a digital 3D model which is also suitable for 3D printing is more time-consuming than the other technologies mentioned. Lastly, this technology uses X-rays and outputs greyscale values linked to the attenuation of different materials in the object. Metal is highly attenuating and therefore introduces image artifacts in the reconstruction, which makes 3D printing the model problematic. This means that other features that contribute to an artwork's material appearance are not included in the scan, such as its colors. Yet, projects such as the collaboration between the Centrum Wiskunde & Informatica (CWI, Center for Mathematics & Computer Science, Amsterdam)'s FleX-ray Lab and the Rijksmuseum (Amsterdam) reveal that these types of scans can be interesting for getting high-quality 3D information about both the inside and the outside of objects. The scan of the *Holy woman with lantern* of the Rijksmuseum, Amsterdam, shows that this method makes it possible to record and digitize complex shapes and show the internal structure (**Figure 7**). Furthermore, they show that surface scans can be added to the CT data, thus overcoming the issue that CT scanning does not record the object's material appearance [41, 42].

Figure 7.
(a) Holy woman with lantern, Rijksmuseum collection BK-NM-9253, (b) 3D rendering and orthogonal slices through the 3D reconstruction showing the internal structure (tree rings). Through the CT scan, this object could be dated using dendrochronological methods. Photo credits: Francien Bossema.

5. 3D printing artworks

After having captured an artwork digitally, 3D printing can be used to materialize it. Right now, although 3D printing is still developing and has certainly not reached its peak capacity, there are various methods with which one can create three-dimensional shapes, according to ISO/ASTM [43, 44]:

- Vat photopolymerization (VP)
- Material extrusion (ME)
- Material jetting (MJ)
- Binder jetting (BJ)
- Powder bed fusion (PBF)
- Directed energy deposition (DED)
- Sheet lamination (SL)

To convincingly reproduce an artwork using 3D print and match its esthetical qualities, there are a few requirements to be met by the method of choice:

- Full color and appearance control should be supported;
- High resolution should be guaranteed;
- The printing material and technique should imitate the artwork's material appearance as best as possible.

Based on these requirements, VAT photopolymerization, directed energy deposition, and sheet lamination can be excluded right away. Although material extrusion does not meet these requirements either, it is, however, frequently used in the CH field because it is easy to use and low cost. The method has been used when polychromy or high-quality resemblance is not a requirement, for example, when creating replicas for education purposes. In terms of high-resolution, full color, and appearance control, material jetting, binder jetting and powder bed fusion could meet all three requirements to a certain degree.

5.1 Material jetting

Like material extrusion, material jetting creates an object layer by layer until the right height is reached. However, instead of using a spool of one material, it uses multiple inkjet nozzles—similar to the one used by regular paper printers—with which individual droplets of different colors and materials are selectively deposited [44]. Furthermore, material jetting uses photosensitive polymer instead of thermosensitive polymer [45]. This means that the liquid ink does not harden as it cools off, but instead, a UV light is used to solidify the individual droplets [46]. This results in a method that allows a high level of detailing and in which a large range of colors, materials, glossiness, gradients, and transparencies can be used, making it a more suitable technology in the case of reproducing near flat artworks such as paintings and low-bas reliefs. However, a downside to using various photosensitive materials is the fact that their products are more sensitive and brittle, which means that these prints are considerably less durable and functional.

5.2 Binder jetting

Similar to material jetting, this type of jetting uses a printer head with multiple nozzles depositing droplets of liquid ink(s) onto a printer platform, making it possible to print high-quality and polychrome three-dimensional objects [47]. However, this process differentiates from material jetting as it does not use the solidification of photosensitive materials. Instead, a liquid bonding agent, which functions as a sort of glue, is deposited to bind the powdered particles together [44, 45]. Because the powder is used as a basis, the materials suitable for this type of printing are limited: Only finely granulated ceramics, sand, and metals are suitable for this technology. Furthermore, because these small particles are glued together instead of heated together, there are no new chemical bonds forged between the individual components. For this reason, these prints are porous and their surface finish is rough and grainy, which also results in lesser color quality [46]. These elements make this technology less useful for 3D reproducing paintings as the right material appearance and "feel" can hardly be achieved. Yet, for the reproduction of statues or artworks made of stone, this method can be considered suitable.

5.3 Powder bed fusion

Like binder jetting, powder bed fusion uses granulated materials as its base material. However, the difference lies in the solidification of the material [44, 45]. Whereas binder jetting uses a bonding agent in liquid form, with powder bed fusion, the heat of a laser is used to melt and/or cure the layer of powder. The advantage of using a heat source to bind materials instead of a "glue" is that a larger variety of materials can be used to create more durable high-quality reproductions (e.g., titanium, aluminum, nylon) as they have been chemically bonded together [47]. However, like binder jetting, the result is grainy and rough. Furthermore, because the melting of materials is used, it is hard, if not impossible, to integrate color within the AM process [48]. Because of this reason—the limited use of materials and the graininess of the end product—powder bed fusion is currently not as suitable for 3D reproducing all types of artworks (e.g., paintings). Yet, for the reproduction of statues or artworks made of stone, this method can be considered suitable.

As this overview shows, there are various ways of 3D printing artwork. However, the categories mentioned here are arbitrary and can change rapidly over time as new technologies enter the market and open up new opportunities. 3D printing has just started to move beyond its infancy stage and as such is not completely mature, while still developing. Right now, each technology still experiences some major limitations. For instance, most 3D printing technologies are still commonly limited to one color, which is the same as its printing material [46]. Furthermore, the limitation of using just one material makes it hard to vary in transparency and opacity between individual layers. Although some techniques offer polychrome printing or the use of multiple inks, the production of realistic colors or surface effects is still hard as it requires extra finishing processes to give synthetic material the desired appearance. Particularly, in the case of CH and the reproduction of art, color printing and resolution are hurdles to overcome as accuracy, good quality, high resolution, and the right material feel are often a top priority for correctly curating narratives with these delicate artifacts [8]. However, it is worth noticing that larger companies such as Hewlett-Packard (HP) have taken on the challenge of developing new technologies to overcome these issues [49]. Since 2016 CE, HP has been working on Multi Jet Fusion printing, a method with which full-color 3D printing with a larger variety of materials is starting to become possible [50]. This way, powder bed fusion might be able to compete with material jetting in terms of material properties and appearance as it would meet the most basic requirements for creating a 3D reproduction of art, namely the ability to print color and varying appearance.

Aside from the lack of aesthetic quality in trying to print in full color, currently, there is still a lot of manual work and technical knowledge needed to create and print a 3D printable model [47]. This makes the method expensive, exclusive, and time-consuming. Furthermore, the standardization of the process and, consequently, guaranteeing continuous product performance remains challenging and one to be overcome [48]. Nevertheless, right now, the main focus of the 3D printing realm will largely remain on the integration of 3D printing in the use and production of parts and products. Moreover, it is discussed that in the future, the exploration of the materials which can be used in 3D printing to convincingly express the object's materials, colors, "feel" and, additionally, to understand 3D printing's materials behavior in the longer term might gain more interest [47, 48].

6. Enabling technologies

Although 3D scanning and 3D printing are useful in understanding and mimicking an object's current appearance, they cannot fabricate its past and/or future material state. Understanding the way an object looks and what it has looked like over time cannot solely be attributed to what is currently visible on the surface. Artwork consists of layers of many different elements (e.g., its canvas, underdrawings, the various types of paint, and varnish) that mostly remain invisible to the naked eye. Moreover, due to external factors such as exposure to light, humidity and careless handling resulting in mechanical losses, an artwork's appearance can change more rapidly and in different ways. These internal and external effects that take place on a molecular and surface level attribute to the optical changes in the artwork's materials, such as its colors, relief, glossiness, and the transparency of individual layers. Because 3D printing uses digital modeling to materialize artworks, this information together with other digital technologies may be used to manipulate, alter, and change this information. This section will discuss the technologies that currently attribute to the possibility of reconstructing and predicting the past and future states of the same artwork.

6.1 Material analyses methods

Recently, there is a growing involvement of scientific methods in the art world which make it possible to visualize elements that have remained invisible for centuries. The first signs date back to the 1930s CE when X-radiography (IR) was undertaken for the analysis of paintings for the first time. Later, thanks to Dutch physicist van Asperen de Boer's research in the 1960s CE, infrared reflectography (IRR) made it possible to see through a painted surface or a painting's upper layers and analyze its underdrawings [51]. This non-invasive process involves analysis with an infrared camera, which uses light in the near-infrared region of the electromagnetic spectrum. Simply put, as an object consists of layers where each one is covering the other, infrared light decreases the opacity of most pigments [52]. One element that is highly infrared absorbent is carbon black, which is often used by artists to sketch the initial design [53]. Using IR, the artist's creative process or sometimes even an entirely different painting can be revealed. This was the case with Vincent van Gogh's *Still life with meadow flowers and roses* (1886–1887 CE), where X-ray scanning revealed a scene of two wrestling men hidden underneath the visible paint layers [54].

In the following decades, many other, more scientific analysis methods providing more information on an artwork's materials would follow, such as dendrochronology, paint sampling, neutron activation audio radiography (1970 CE), and cross-sectional fluorescent staining (1980 CE) [55]. However, these technologies were still not very visually appealing and understandable for the majority of people working with CH objects. This changed with macro-X-ray fluorescence scanning (macro-XRF). Already existing since the beginning of the 1930s CE, this technology only very recently started to attract the attention of art historians, scholars, and conservators as computers and visualization technologies have become increasingly better [56]. By focusing an X-ray beam on a designated area, the emitted fluorescence radiation of individual materials can be measured and analyzed, offering a new non-invasive way of studying paintings based on their material components [57]. The added value of macro-XRF in comparison with the beforementioned and more traditional imaging techniques (e.g., the beforementioned X-radiography and IR) relies on the fact that with this method information on the artwork's composition and the identification of multiple material components can be collected and visualized simultaneously instead of individually [53]. Consequently, the visual relationship of each layer of material becomes clearer.

Nowadays, thanks to the development of digital technology we have succeeded in creating understandable and easy-to-use tools with which we can navigate this information. This way, these imaging technologies have been transformed into mobile instruments that can be deployed in museums, galleries, or conservation studios, which increases the availability of these techniques. For example, Robert Erdmann (professor at the University of Amsterdam and senior scientist at the Rijksmuseum) has created an app with a "curtain viewer," with which you can look at and interact with the visualized results of various material scans (e.g., IR, IRR), research and treatments of Jheronimus Bosch' *Saint Wilgefortis Triptych* (1500–1504 CE), and many other paintings [58].

The large-scale application of these scientific methods and the unveiling of many artworks' materials still have to take place.[4] Yet, the fact that we can look through an object's layers, dissect each material component present in the artwork, and calculate how its materials change or have changed, undeniably changes our perception of artworks and art history. With the increasing power of computers, improvement of visualization technologies, and the growing efficiency with which neural and deep learning networks can be applied to this data, it will be a matter of time before it will become possible to predict and visualize what an artwork's material may have looked like in the past or what it will look like in the future. A successful example is a

[4] Although this overview mentions some material examination technologies used for the analysis of paintings, it most certainly does not cover all available methods. For more information, see: Stoner and Rushfield, Conservation of Easel Paintings.

reproduction of Rembrandt van Rijn the *Night Watch's* missing panels (2021 CE) [59]. Artificial neural networks were used to train a computer to recreate the missing pieces based on a still-existing sketch of the entire artwork. The following part sheds light on the current developments within the field of artificial intelligence.

6.2 Artificial intelligence

Ever since artist Harold Cohen created *AARON* in 1960 in which he tried to code the act of drawing, AI's influence on the art field has been undeniable [60]. Examples like Obvious' series of portraits of the fictive Belamy family (2018 CE) show that with AI and machine learning, one can construct entirely new works of art (**Figure 8**) [61]. The application of neural networks and AI are numerous, yet the focus will be limited to generative methods for they can be considered the most relevant and influential for 3D printing artworks.

Being the most popular and most developed method in the art field hitherto, generative visualization models are capable of generating new examples that plausibly could have been drawn from the original dataset, simply put. Such models are trained to recognize the regularities or patterns in the data it is fed in an unsupervised manner [62]. Previously, generative adversarial network (GAN), variational autoencoder (VAE), and flow-based models have been used (e.g., GAN was used for the construction of the Belamy portraits), yet their influence in the art world has remained limited for they were unstable, complex, or too hard to use [63]. However, this has changed due to the recent development of diffusion models which use a neural network that denoises images blurred with Gaussian noise and reverses the diffusion process. They steer the diffusion process with information learned from image-caption pairings gathered from the internet. This allows them to generate images conditioned on a text prompt. The influence of AI within the field of art has taken flight. Imagen,

Figure 8.
Edmond de Belamy, Obvious, 2018 CE, digital artwork.

DALL-E2, Midjourney, and other open-source diffusion systems show that it has become possible to easily and rapidly generate new images and artworks based on simple concepts and keywords [64–66]. Evidently, these generative visualizations are interesting for creating new works of art and for experimentation. Yet, by supplementing the right data (e.g., based on material research or by uploading a large set of artworks by one artist) they can also become a helpful tool to get an understanding of an artwork, the way an artist has worked and to predict what an artwork must have looked like at some point, as is exemplified by the previously mentioned reconstruction of the *Night Watch*.

However, artworks are not two-dimensional. Hitherto, many models, including diffusion models, use operations that are well-defined on a flat domain with a regular grid, such as images or voxel grids. However, many disciplines work with data that lies on a curved or stretched surface (e.g., the canvas of a painting or the surface of a sculpture) or data that has no spatial embedding, such as citation graphs or friendship networks. Geometric deep learning attempts to transfer deep learning techniques from Euclidean space to non-Euclidean domains [67], thereby allowing for the models to work more closely with real-world data, including 3D data such as meshes and point clouds. The developments have not been as fast as is the case with generative visualizations. One reason is the fact that a three-dimensional space is rather complex and a large quantity of data are necessary to generate one single 3D object, which is not as readily available as is the case with Euclidean data. The neural network in a NeRF is optimized to best represent existing views of a 3D scene and can be sampled continuously from new viewing directions [68]. NeRF can generate new views of 3D scenes, by using partial sets of 2D images from angles along with the corresponding positions from which the images are taken [69]. By using a rendering loss, the input views of a scene can be reproduced. Currently, NeRF is still computationally-intensive.[5] Yet, new algorithms are consistently improving their performance, making it more accessible. This way, it will become easier and faster to scan, store, and share 3D information. Thus, more 3D CH objects can become available online, which is beneficial for training neural networks in the future. Furthermore, the quick and easy rendering of 3D models could make the computer-aided design (CAD) process used for 3D printing easier and more accurate. Subsequently, as *The Next Rembrandt* (2016 CE) shows, AI combined with 3D printing could lead to the creation of entirely new works of art in the style of a well-known artist [70].

It must be emphasized, though, that the term "AI" in these examples often means that an algorithm is *data-driven*. There are examples of "smart" algorithms, yet they do not fall under the term AI. The techniques that are now known as AI are often algorithms that are optimized on a dataset. This is not necessarily the case with traditional algorithms: Each step is then programmed and determined based on theory or analysis (and sometimes arbitrariness). Keeping this in mind, it is important to realize that the application of AI in the art world is often complimented by existing and more traditional tools, such as methods in computer graphics and geometry. An example of this is a tool that helps to naturally pose human bodies [71]. Previously, each arm and/or leg had to be placed in exactly the right place. Adding a data-driven tool that has been trained on many human poses makes it easier to generate a pose based on an "expected" natural pose. In this way, combining data-driven AI with

[5] NeRF uses images representing a scene and interpolates these images in order to render one complete scene. This way, a NeRF network directly maps from viewing direction and spatial location (5D input) to opacity and color (4D output).

these classical tools will make it easier to show examples and automate tasks that otherwise required a lot of expertise and mathematical knowledge. This will make the 3D printing process easier and more accessible to the art field. Furthermore, as Case Western Reserve University shows, a neural network can be trained to distinguish and generate different painters' brush strokes in both 2D and 3D [72]. This way, combining data-driven AI with methods in geometry helps predict lost information about an artwork or generate past or future versions of existing artworks, which can be physicalized with 3D printing. For instance, the color and geometry of the pounces in the background of the medieval *Crucifixion* of the Lindau Master (c. 1425 CE) can be reconstructed and 3D printed the way it must have looked before the blue azurite layer was applied (**Figures 9** and **10**) [73]. A painting like Johannes Vermeer's *Girl with a Pearl Earring* (1665 CE) can be 3D printed without a craquelure pattern. Furthermore, using a neural network trained in identifying Rembrandt's brushstrokes could help reconstruct the flattened surfaces in *Study of an Old Man* (1650 CE) and the artwork can be 3D printed the way it must have looked like.

Yet, there are still some obstacles to overcome. Currently, to be able to generate a 3D object with AI, one needs a very large dataset to compensate for information that has not been recorded. Unlike the case with generative visualization models based on Euclidean data, 3D data is not as easily accessible nor available in large quantities. The digitalization of artworks and open-access sharing of these data are not yet a common practice in museums and galleries. This way, generating entire 3D objects is still hardly possible. What seems more likely soon, however, is automatically adding a 2D texture map to a 3D mesh or a topography map. Furthermore, it must be emphasized that these generated visualizations and 3D objects will always be partly based on

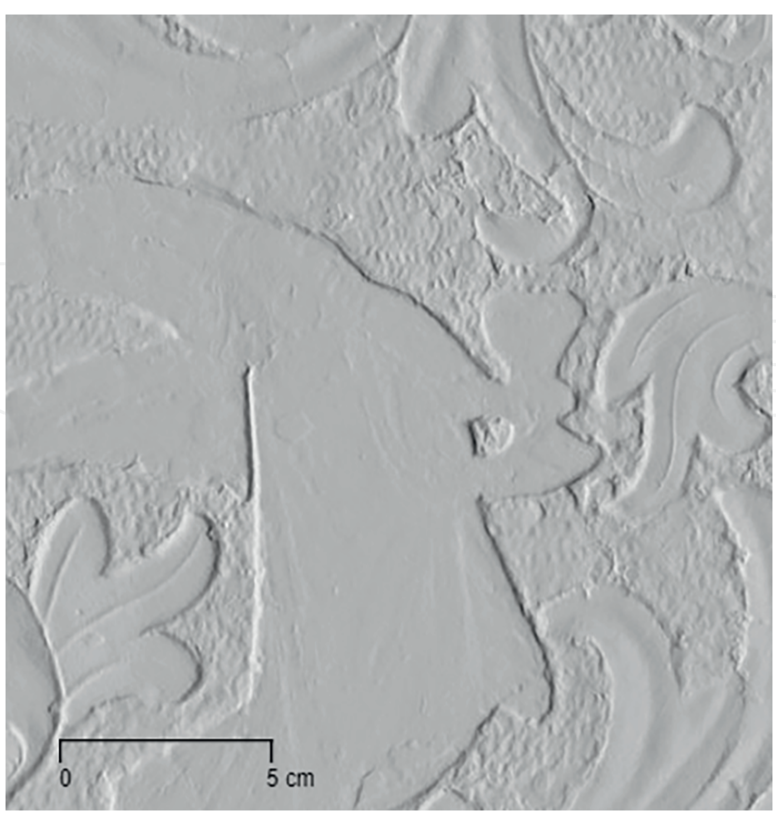

Figure 9.
Master of the Lamentation of Christ in Lindau, The Crucifixion, ca. 1425 CE. Tempera on panel, 125 × 89 cm, Museum Catharijneconvent, 3D detail without color the way the painting looks now.

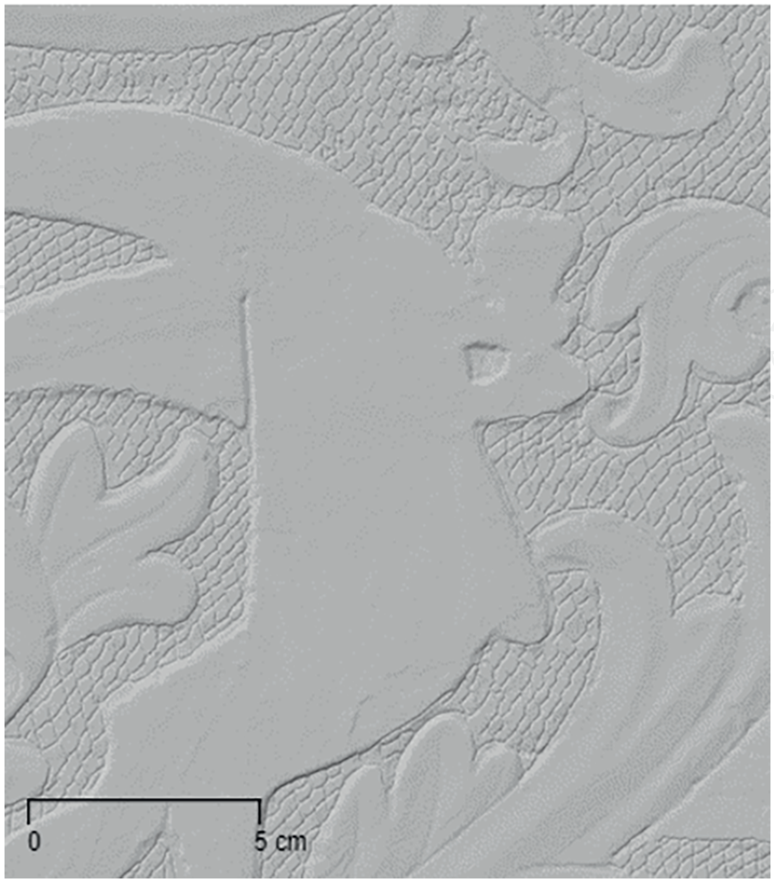

Figure 10.
Reconstruction of the pattern in the background. Photo credits: Ruben Wiersma.

estimates, predictions, the data supplemented, and the algorithm itself. Therefore, it might thus not be suitable for scientific research purposes in all cases.

Nevertheless, as 3D scanning and printing technology also improves which aids the digitalization of more objects, one could imagine how these developments combined with AI would yield far more accurate and precise results in the future. Furthermore, with the growing influence of the Metaverse, there is a growing necessity to easily and quickly digitalize objects, pushing the developments within the field. Additionally, with more open-source 3D modeling websites such as Blender and Adobe's Substance 3D and the possibility to experiment with diffusion models, the future impact of AI on the art world is undeniable.

7. Future perspectives

As this chapter has shown, various technologies enable the creation of 3D-printed reproductions of paintings, each attributing to what the final product might look like. It is undeniable that the continuous development of scientific methods within material science will uncover more of the hidden layers of artworks invisible to the naked eye. Furthermore, as computational power will continue to increase, it will become easier to visualize the discoveries made due to material and scientific research and examination. With the help of better neural networks, this could potentially result in better "curtain view"-like applications in which more scans can be integrated and better stitched together in a more user-friendly way. Furthermore, the growth in deep learning systems together with these material examination technologies could potentially attribute to better understanding and predicting the painting's current, past, and future material state. Moreover, as mentioned before, large printing companies will have taken on the challenge of developing new technologies to come up with full-color 3D printing technologies with a larger variety of materials. When more materials become available as a base to print textures on (e.g., canvas) or to print with (e.g., gold and other metals) in a more automated way, 3D reproductions of paintings will become more convincing. This will make the technology more interesting for the art field, as the lack of the right "feel" of the technology is often considered a hurdle to overcome. Furthermore, advancements in better printing materials will make it an interesting method for visualizing the data gathered and potentially manipulated using neural networks and user-friendlier methods, making it a more applicable method for conservation and restoration purposes.

However, the beforementioned increase in computational power is not solely limited to the increasing resolution, better visualization methods, and the data which can be gathered and processed in a short amount of time, but it will undeniably have its effects on other technologies in the digital realm as well. Right now, extended reality (XR) technologies, which is an umbrella term that covers all of the various technologies such as AR, VR, and mixed reality (MR) that enhance our senses by either providing additional information about the material world we live in or by creating entirely simulated worlds, are only at the brim of their existence.[6] Yet, their rapid development together with the advancements within social media and the rise of virtual worlds (e.g., the Metaverse) will make it possible to immerse oneself entirely into online realms that look similar to the "real" world but are computer generated. Although these technologies are not directly involved in the fabrication process of CH objects, they will have their influence on the perception of and engagement with artworks and 3D prints. This growing digitization and digitalization of the world, objects, and artworks around us using 3D technologies make it possible for one to find a variety of options for looking at the same artwork and find easier ways of either digitally or physically engaging with them.[7]

After the increasing digitalization of the world around us and the involvement within the virtual realm, the *non-fungible token* (NFT)—a digital seal of authenticity—is on the rise and becoming increasingly important. In short, an NFT can be seen as a token or a sign which can be used as a validator of ownership and one unique (digital) item. The way an official owner can secure its ownership and the unicity of the digital object is by securing the object with the Ethereum blockchain [74]. This way, it becomes impossible to modify the record or copy-paste its ownership. Right now, digital artworks are already being sold at renowned auction houses such as Christie's, for example, *Beeple's Everydays: The First 5000 Days* which sold in 2020 CE for over 69 million dollars (**Figure 11**) [75]. Not only can digital models and data become valuable by themselves, but it also becomes possible to transform material artworks into valuable digital formats. This happened for example, with Banksy's print called Morons, where a collective called BurntBanksy filmed the destruction of the original material artwork and sold the

[6] Augmented reality (AR): adds a layer of digital elements and/or information to a live situation, usually by using a smartphone. Virtual reality (VR): creates a complete immersive experience shutting out the physical world completely, usually by wearing VR glasses. Mixed reality (MR): includes the interaction of elements of both AR and/or VR, real-world and digital objects.

[7] Digitization: the conversion from an analogue format to a digital version. Digitalization: making digitized workable. This way, the digitized information is converted in a way to make processes more effective or productive.

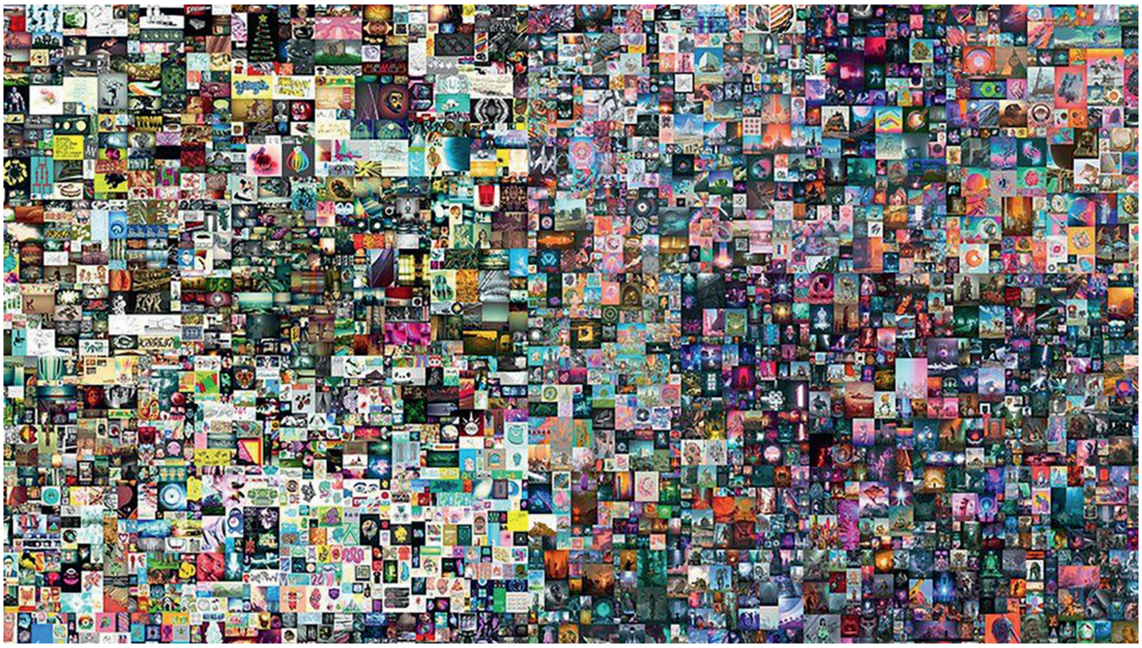

Figure 11.
Everydays: The First 5000 Days, Beeple, 2007–2020 CE, digital artwork.

video as an NFT [76]. A similar case has happened with a drawing by Frida Kahlo [77]. Furthermore, artists like Damien Hirst have also started to sell their art similarly [78]. In this way, the artwork's value or authenticity has moved from the physical manifestation to a digital form as an NFT. What this development will mean in the case of the 3D models, digitized paintings and cultural heritage objects are that they may become valuable and highly prized assets existing next to the material original artwork and outside of cultural institutions and museum walls and authority. Moreover, it could mean that they could potentially take over the "aura" of the existing artworks.

With the potential rise of the value of these 3D digital art models caused by phenomena such as NFTs, questions can arise about the actual ownership of the 3D scanned objects under study. Currently, there is no clear idea to which these data belong: would this be the museum that owns the original artwork, the person(s) behind the scanning, or the computer processing the data? This could lead to potential issues regarding the intellectual property rights of the scanned data and future 3D prints. Although this is an interesting and important facet of 3D printing's development, the legal and copyright-related questions fall out of the scope of this particular research.

Right now, it is hard to predict how these technologies will change or have changed the perception of artworks exactly. However, discoveries thanks to material research, alterations made with the help of artificial intelligence, and the translation of this information into high-quality 3D printed reproductions could drastically change art history at large. A parallel can be drawn with the perception of dinosaurs. Until recently, the prevalent idea was that dinosaurs must have looked like reptiles with scales and that they were rather tough looking. Yet, as a result of research and by discovering feathers in fossils, the whole idea of their physical appearance changed drastically: They might have looked more like birds, feathered, and possibly brightly colored. In the case of 3D printing artworks, the same thing could be said: We believe that what we know now is "authentic" and "real," yet discoveries and revelations due to these technologies combined with 3D printing can and will drastically change what we consider to be the truth in the future.

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References

[1] The Economist. Print Me a Stradivarius—How a New Manufacturing Technology will Change the World. 2011. Available from: https://www.economist.com/node/18114327/.%21%21?page=2 [Accessed: September 1, 2022]

[2] Elkhuizen W et al. Digital Manufacturing of Fine Art Reproductions for Appearance. Delft: TU Delft; 2018

[3] Tissen LNM. Authenticity and Meaningful Futures for Museums: The Role of 3D Printing. In: Journal of the LUCAS Graduate Conference. Leiden: Leiden University; 2021. pp. 94-122

[4] Benjamin W. The Work of Art in the Age of Mechanical Reproduction. London: Penguin Books; 2008

[5] Malik US, Tissen LNM, Vermeeren APOS. 3D reproductions of cultural heritage artefacts: Evaluation of significance and experience. In: Studies in Digital Heritage. 4th ed. Bloomington: Indiana University; 2021. pp. 24-28. ISSN: 2574-1748

[6] Gao Q, Jones S. Authenticity and Heritage Conservation: Seeking Common Complexities beyond the "Eastern" and "Western" Dichotomy. International Journal of Heritage Studies. 2021;**2021**:90-106

[7] Lowe A. The Aura in the Age of Digital Materiality—Rethinking Preservation in the Shadow of an Uncertain Future. Milan: Silvana Editoriale; 2020

[8] Tissen LNM, van Veldhuizen MJ. Picture-Perfect—The Perception and Applicability of Facsimiles in Museums: Art & Perception. Leiden: Brill; 2022

[9] Tissen LNM. 3D Printing Works of Art: An Opportunity or Nightmare for Curators. CODART. 2022. Available from: https://www.codart.nl/feature/museum-affairs/3d-printing-works-of-art-an-opportunity-or-nightmare-for-curators/ [Accessed: October 22, 2022]

[10] Scopigno R et al. Digital fabrication techniques for cultural heritage: A survey: Fabrication techniques for cultural heritage. Computer Graphics Forum. 2017;**2017**:1-6

[11] Neumüller M et al. 3D Printing for Cultural Heritage: Preservation, Accessibility, Research and Education. Heidelberg: Springer; 2014

[12] Ballarin M, Balletti C, Vernier P. Replicas in cultural heritage: 3D printing and the museum experience. In: ISPRS—International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. Göttingen: Copernicus GmbH; 2018. pp. 55-62

[13] Acke L et al. Survey and literature study to provide insights on the application of 3D technologies in objects conservation and restoration. Journal of Cultural Heritage. 2021;**49**:1-15

[14] Beentjes TPC. Casting Rodin's Thinker. Sand Mould Casting, the Case of the Laren Thinker and Conservation Treatment Innovation. Amsterdam: University of Amsterdam; 2019. pp. 281-288

[15] Van Gogh Museum. Restauratie "Zeegezicht Bij Scheveningen". 2019. Available from: https://www.vangoghmuseum.nl/nl/over/kennis-en-onderzoek/restauraties/restauratie-zeegezicht-bij-scheveningen [Accessed: October 22, 2022]

[16] How 3D Printing Brings Antiquities Back to Life. Formlabs. 2018. Available

at: https://formlabs.com/blog/how-3d-printing-brings-antiquities-back to-life/ [Accessed: October 22, 2022]

[17] Speranza L. The Gap between Ethics and Aesthetics in Italian Restoration: Experiences in Laboratories of the Opificio Delle Pietre Dure in Florence—Della Robbia Sculpture Case Studies. Washington D.C.: American Institute for Conservation of Historic and Artistic Works. 2017

[18] Van Apeldoorn N. 3D Reconstruction of Niniveh. Delft: TU Delft; 2017

[19] Scanning for Syria Project. Global Heritage and Development. 2015. Available from: https://www.globalheritage.nl/news/scanning-for-syria-project. [Accessed: October 22, 2022]

[20] Factum Foundation. The Thomb of Seti: Recording and Facsimile. Available from: https://www.factumfoundation.org/pag/1502/the-tomb-of-seti-recording-and-facsimile. [Accessed: October 22, 2022]

[21] Elkhuizen W et al. A 3D Printed Reconstructing of a Painting's Original Size: Showing the Original Size of Saul and David by Rembrandt. Barcelona, Spain; 2016

[22] Smithsonian Institute 3D Digitization. Available from: https://3d.si.edu/ [Accessed: October 22, 2022]

[23] Uffizi in 3D. Available from: https://sketchfab.com/tags/uffizi. [Accessed: October 22, 2022]

[24] The National Museum of Antiquities. Available at: https://sketchfab.com/rmo_leiden. [Accessed: October 22, 2022]

[25] Mauritshuis. Facelifts En Makeovers. 2022. Available from: https://www.mauritshuis.nl/nu-te-doen/tentoonstellingen/tentoonstellingen-uit-het-verleden/facelifts-makeovers/ [Accessed: October 22, 2022]

[26] Knapp M, Wolff R, Lipson H. Developing printable content: A repository for printable teaching models. In: Proceedings of the 19th Annual Solid Freeform Fabrication Symposium. Austin, TX; 2008

[27] Victoria & Albert Museum. Taking Sculptures for a Walk: 3D Printing and Museum Outreach. Available from: https://www.vam.ac.uk/blog/digital/taking-sculptures-for-a-walk-3d-printing-and-museum-outreach [Accessed: October 22, 2022]

[28] Menano L et al. Integration of 3D printing in art education: A multidisciplinary approach. Computers in the Schools. 2019;**3**:222-236

[29] Factum Foundation. The Materiality of the Aura. New Technologies for Preservation. 2019. Available from: https://www.factumfoundation.org/pag/1598/. [Accessed: October 22, 2022]

[30] Museum Boijmans van Beuningen. Sgraffito in 3D. 2009. Available from : https://www.boijmans.nl/tentoonstellingen/sgraffito-in-3d [Accessed: October 22, 2022]

[31] Balletti C, Ballarin M, Guerra F. 3D printing: State of the art and future perspectives. Journal of Cultural Heritage. 2017;**26**:176-178

[32] Cantoni V et al. Art Masterpieces Accessibility for Blind and Visually Impaired People. In: Computers Helping People with Special Needs. Cham: Springer International Publishing; 2018. pp. 267-274

[33] Solly M. This Replica of a Tlingit Killer Whale Hat Is Spurring Dialogue

About Digitization. Smithsonian Magazine. 2017. Available from: https://www.smithsonianmag.com/smithsonian-institution/replica-tlingit-killer-whale-hat-spurring-dialogue-about-digitization-180964483/. [Accessed: October 22, 2022].

[34] Daneshmand M et al. 3D Scanning: A Comprehensive Survey. New York: Cornell University. 2018. DOI: 10.48550/arXiv.1801.08863

[35] Akca D et al. High Definition 3D-Scanning of Arts Objects and Paintings, Zürich; 2007. DOI: 10.3929/ethz-a-005748653

[36] Elkhuizen WS et al. Reproduction of gloss, color and relief of paintings using 3D scanning and 3D printing. In: Eurographics Workshop on Graphics and Cultural Heritage, Barcelona; 2017. pp. 183-187

[37] Tissen LNM et al. Using 3D scanning to support conservation treatments for paintings. In: Materials Science and Engineering. Bristol: IOP Publishing; 2020

[38] Rakitina E et al. An overview of 3D laser scanning technology. In: Proceedings of the International Scientific Conference. Chiteseer; 2008

[39] Means BK. 3D recording, documentation and management of cultural heritage. Historical Archieves. 2017;**51**:582-583

[40] Elkhuizen WS et al. Comparison of three 3D scanning techniques for paintings, as applied to Vermeer's "Girl with a Pearl Earring". Heritage Science. 2019;7:5-9

[41] Bossema FG et al. Integrating expert feedback on the spot in a time-efficient explorative CT scanning workflow for cultural heritage objects. Journal of Cultural Heritage. 2021;**49**:38-47

[42] Domínguez-Delmás M et al. Dating and provenancing the Woman with lantern sculpture – A contribution towards attribution of Netherlandish art. Journal of Cultural Heritage. 2021;**50**:179-187

[43] ISO/ASTM. 52900:2015 Additive Manufacturing—General Principles—Terminology. 2015. Available from: https://www.iso.org/obp/ui/#iso:std:iso-astm:52900:ed-1:v1:en. [Accessed: October 22, 2022]

[44] ISO/ASTM. Additive Manufacturing e General Principles e Part 2: Overview of Process Categories and Feedstock. 2022. Available from: https://www.iso.org/standard/61626.html [Accessed: October 22, 2022]

[45] Yuan J et al. Accurate and computational: A review of color reproduction in full-color 3D printing. Materials & Design. 2021;**209**:109943

[46] Doubrovski EL. Design Methodology for Additive Manufacturing: Supporting Designers in the Exploitation of Additive Manufacturing Affordances. Delft: TU Delft; 2016

[47] Deshmukh K et al. Chapter 1—Introduction to 3D and 4D printing technology: State of the art and recent trends'. In: Sadasivuni KK, Deshmukh K, Almaadeed MA, editors. 3D and 4D Printing of Polymer Nanocomposite Materials. Amsterdam: Elsevier; 2020. pp. 1-24. DOI: 10.1016/B978-0-12-816805-9.00001-6

[48] Wang X et al. Color reproduction accuracy promotion of 3D-printed surfaces based on microscopic image analysis. International Journal of Pattern Recognition and Artificial Intelligence. 2020;**34**(01):2054004

[49] Molitch-Hou M. Overview of additive manufacturing process. In:

Zhang J, Jung Y, editors. Additive Manufacturing. Oxford: Butterworth-Heinemann; 2018. pp. 1-38. DOI: 10.1016/B978-0-12-812155-9.00001-3

[50] HP. HP Multi Jet Fusion Technology. Available from: https://www.hp.com/us-en/printers/3d-printers/products/multi-jet-technology.html [Accessed: October 22, 2022]

[51] Legrand S et al. Examination of historical paintings by state-of-the-art hyperspectral imaging methods: From scanning infra-red spectroscopy to computed X-ray laminography. Heritage Science. 2014;**2**(1):1-8

[52] Groen K. Paintings in the Laboratory: Scientific Examination for Art History and Conservation. Amsterdam: University of Amsterdam; 2011. pp. 26-28

[53] The National Gallery. Infrared. Glossary. Available from: https://www.nationalgallery.org.uk/paintings/glossary/infrared. [Accessed: October 22, 2022].

[54] Kröller Müller. Stilleven Met Akkerbloemen En Rozen. Available from: https://krollermuller.nl/en/vincent-van-gogh-still-life-with-meadow-flowers-and-roses. [Accessed: October 22, 2022]

[55] Hermens E. Technical art history: A synergy of art, conservation and science. In: Art History and Visual Studies in Europe: Transnational Discourses and National Frameworks. Leiden: BRILL; 2012

[56] Stoner JH. Turning points in technical art history. In: American Art. Chicago: University of Chicago; 2012

[57] Stoner JH, Rushfield R. Conservation of Easel Paintings. In: Routledge Series in Conservation and Museology. London: Routledge; 2020. pp. 317-318

[58] Saint Wilgefortis Triptych. Curtain viewer showing visible light, infrared photography, and infrared reflectography from before restoration. Available from: http://boschproject.org/view.html?layout=top-major&mode=curtain&pointer=0.5,0.5&i=23_24_25_MCPVIS%5Bl=visible%20light%20photography%5D,23_24_25_MCPIRP%5Bl=infrared%20photography%5D,23_24_25_IRREFL%5Bl=infrared%20reflectography%5D [Accessed: October 22, 2022]

[59] Rijksmuseum. Nachtwacht de Missende Stukken. 2020. Available from: https://www.rijksmuseum.nl/nl/stories/operatie-nachtwacht/story/nachtwacht-de-missende-stukken [Accessed: October 22, 2022]

[60] Cohen H. The further exploits of Aaron, Painter. Stanford Humanities Review. 1995;**4**(2):1-18

[61] Obvious. La Famille de Belamy. 2019. Available from: https://obvious-art.com/la-famille-belamy/. [Accessed: October 22, 2022]

[62] Geng X, Kang BH. PRICAI 2018: Trends in Artificial Intelligence: 15th Pacific Rim International Conference on Artificial Intelligence, Nanjing, China, August 28-31, 2018, Proceedings, Part I. In: Lecture Notes in Computer Science. Berlin, Heidelberg: Springer; 2018

[63] Bond-Taylor S et al. Deep Generative Modelling: A Comparative Review of VAEs, GANs, Normalizing Flows, Energy-Based and Autoregressive Models. New York: IEEE Transactions on Pattern Analysis and Machine Intelligence. 2021

[64] Imagen. Available from: https://imagen.research.google/ [Accessed: October 22, 2022]

[65] Dall-E 2. Available from: https://openai.com/dall-e-2/ [Accessed: October 22, 2022]

[66] Midjourney. Available from: https://www.midjourney.com/home/ [Accessed: October 22, 2022]

[67] Bronstein MM et al. Geometric deep learning: Going beyond Euclidean data. IEEE Signal Processing Magazine. 2017;**34**(4):18-42

[68] Barron JT et al. Mip-Nerf: A Multiscale Representation for Anti-Aliasing Neural Radiance Fields. New York: IEEE Transactions on Pattern Analysis and Machine Intelligence. 2021. pp. 5855-5864

[69] Mildenhall B et al. Nerf: Representing scenes as neural radiance fields for view synthesis. Communications of the ACM. 2021;**65**(1):99-106. DOI: 10.1145/374308.374363

[70] The Next Rembrandt. 2015. Available from: www.thenextrembrandt.com. [Accessed: October 22, 2022]

[71] Bocquelet F et al. AI and Physics Assisted Character Pose Authoring. New York, NY, USA: Association for Computing Machinery; 2022

[72] Ji F et al. Discerning the painter's hand: Machine learning on surface topography. Heritage Science. 2021;**9**(1):2-22

[73] Tissen LNM, Frequin S, Wiersma RT. The case of the golden background, a virtual restoration and a physical reconstruction of the medieval crucifixion of the Lindau Master (c. 1425). Digital Humanities Quarterly. 2022;**16**(2):1-16

[74] Nadini M et al. Mapping the NFT revolution: Market trends, trade networks, and visual features. Scientific Reports. 2021;**11**(1):1-11

[75] Christies. Beeple's Opus Created over 5,000 Days by the Groundbreaking Artist, This Monumental Collage Was the First Purely Digital Artwork (NFT) Ever Offered at Christie's. 2021. Available from: https://www.christies.com/features/Monumental-collage-by-Beeple-is-first-purely-digital-artwork-NFT-to-come-to-auction-11510-7.aspx. [Accessed: October 22, 2022]

[76] Tissen LNM, Frequin S. Digitalisering van Kunstwerken Is van Waarde, Maar Waak Voor Cowboys En Destructie van de Kunstmarkt. Amsterdam; 2021. Available from: https://www.volkskrant.nl/cultuur-media/digitalisering-van-kunstwerken-is-van-waarde-maar-waak-voor-cowboys-en-destructie-van-de-kunstmarkt~bb96615b/?referrer=https%3A%2F%2Fwww.google.com%2F [Accessed: October 22, 2022]

[77] Renders W. Miljonair Verbrandt Tekening van Frida Kahlo, Om Die Als NFT Te Kunnen Verkopen. Amsterdam; 2022. Available from: https://www.volkskrant.nl/nieuws-achtergrond/miljonair-verbrandt-tekening-van-frida-kahlo-om-die-als-nft-te-kunnen-verkopen~bc8d827b/ [Accessed: October 22, 2022]

[78] Holland O, Dolan L. "That Is Art!": Damien Hirst Has Begun Burning Thousands of His Own Paintings. London: CNN; 2022