Digital Fabrication for Cultural-Heritage Enhancement:

A Tale of Three Projects

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Digital Fabrication for Cultural-Heritage Enhancement – an Introduction

Digital fabrication (DF) is the method of using computational technology to produce "almost anything" with high efficiency. The DF movement took advantage of the digital revolution (Gershenfeld, Gershenfeld, and Cutcher-Gershenfeld 2017). The aim of this technology is to reduce the necessary skills and costs of manufacturing (Cutcher-Gershenfeld, Gershenfeld, and Gershenfeld 2018). This technology can work in a variety of fields and scales as well as with many materials (Pham and Gault 1998; Lim et al. 2012).

Gershenfeld described the development of DF methodology. He described the history of DF and dated it back in 1952 when the first numerical control machine was made by John T. Parsons and used to manufacture parts for aircraft. The machine was described as working "by using a computer program instead of a machinist to turn the screws that moved the metal stock." The research continued in developing DF from descendants of Parsons's machine (which became modern computer numerical control (CNC) machines), later enhanced by numerical-control technology (in 3D printing machines) and even avant-garde technology in the so-called digital assembler. In the same work, Gershenfeld pointed out that this way of manufacturing had advantages in being highly reliable, economical, accessible, and materially efficient. Hence, this technology became important in the founding of the Makerspace (FabLab) network – a system of digital artisans (Gershenfeld 2012). FabLabs are places where people from all over the world produce "almost anything", from food, furniture to buildings and vehicles (Cutcher-Gershenfeld, Gershenfeld, and Gershenfeld 2018). At the time we conducted our research, more than 2,500 FabLabs worldwide were registered at the FabFoundation site ("Welcome | FabLabs" n.d.).

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In the field of cultural heritage (CH), DF has been widely used with the aim of enhancing an aura of authenticity, preserving original antiquities, and enhancing accessibility and interactivity. Scopigno (2015) in a survey, categorized this technology by two major techniques: subtractive and additive. Subtractive technologies, mainly including CNC (computer numerical control) machines, usually have high precision, vary in working size, and can work in various types of material, although the materials may be difficult to master. Additive technologies, including 3D-printing technologies, generally cost more than CNC. In return, they can manufacture freeform shapes, including a large range of details.

The advantage of using DF in enhancing CH is that this method can fabricate (1) fast reproduction of objects in various scales; (2) replicas of artwork so that the original antiquities may be borrowed temporarily or permanently replaced, made highly accessible, and be protected while shipping; and (3) supports for restorations; and (4) support storytelling by means of alternative illustrative models in museums or exhibitions (Scopigno et al. 2017; Anagnostakis et al. 2016; Wilson et al. 2017; Kostakis, Niaros, and Giotitsas 2015; Merchán et al. 2019). Other researchers showed that digital fabrication can also be used for art exhibitions (Celani, Pupo, and Piccoli, n.d.; Weiler, Ingalls, and Kuznetsov 2022). At the same time, limitations should be accounted for, particularly working spaces, quality of detail, color, and cost (Scopigno et al. 2017). In a recent review of the state of makerspace, it is noticeable that the amount of research in the CH setting is still small (museums at only 2 percent) compared to the educational setting (public libraries, 9 percent, universities, 14 percent, preK through high school, 19 percent) (Mersand 2021).

Currently, the applications of DF in museums through FabLab center on didacticization and conservation. Nevertheless, DF has proven to have major advantages in design of inclusive and participatory museum experience. In research exploring the role of design in museum experience, Stefania Palmieri et al. (2023) have highlighted the role of digital fabrication in closing the gap between design and production.

Museum design has two main approaches: human-centered and experience design. The first focuses more on inclusivity and accessibility, while the second pays attention to narrativity and visit experience. DF has been mentioned as a support in the development of acquisition, modeling and prototyping technologies, hence broadening CH perspective (Palmieri et al. 2023; Dal Falco and Vassos 2017). In fact, the characteristics achieved in those projects including accessibility, inclusion, education, enjoyment, reflection, are also highlighted in the ICOM definition of the museum

(ICOM 2022). Throughout the cases, our research reveals specific roles of DF in museum and exhibition space design, assessing both human-centered and museum-experience aspects.

The goal of this article is to explore the practical possibility of using various DF techniques, through in-depth historical, archaeological, cultural research, to (1) create a common workflow for applying digital fabrication in three cases and (2) assess their effectiveness through context, objectives, technologies used, inclusivity, and accessibility (human-centered design) as well as interactivity and narrativity (museum-experience design).

Spazio Geco, the FabLab Developing Expertise in Museum Technology

Spazio Geco, the organization implementing projects in the three cases mentioned, is a multidisciplinary FabLab made up of architects, engineers, programmers, art historians, archeologists, communications and cultural-heritage experts, storytellers, and historians ("Spazio Geco," n.d.; Belvedere et al. 2022). Founded in 2013, known for fostering digital manufacturing and open-source technology for application to museology and exhibitions, Spazio Geco has more than ten years of experience in using DF in CH. Referring to the previous advantage of DF in a CH setting mentioned by Palmieri et al. (2023), Spazio Geco generated a workflow of four steps:

1. Acquistion: gather data through documents, 2D and 3D scanning, existing digital data;
2. (Re)modelization: from the data obtained, use 3D-modeling technology to simulate the physical artifact in a digital environment;
3. Prototyping: test different reinterpretation of the replica in real life; and
4. Realization: fabricate the design using DF technology, particularly 3D printing or CNC.

Investigating three case studies implemented by the same makerspace may show the potential in different contexts of using one workflow with similar human resources.

Technology in Action – a Tale of Three Projects

This research describes a process of CH valorization and digital reproduction taking place in three sites with distinctive objectives: (1) a replica for original replacement in the Mummy, (2) reunion and interactivity of artifacts in he Wunderkammer 4.0, and (3) atmospheric representation in

Belgioioso Castle. In each case, this article will interpret the application of the reproductive model in cultural representation and their effects.

Table 1. General information of the project, the Mummy

The Mummy

Project	The Mummy
Year	2017
Client	Museo di Archeologia dell'Università di Pavia, Italy
Goal	Enhancement and accessibility
Scientific partnership	Sabina Malgora, Mummy Project Research; Fondazione IRCC, Policlinico San Matteo.

In 1824, an Egyptian mummy from Cairo was given to the then Gabinetto di Anatomia Umana of the University of Pavia, already unwrapped and outside its original coffin, as was customary in those days. Over the decades, the mummy was relocated several times, first in the Museo di Storia Naturale and later in the Visconti Castle alongside embalmed animals from the Spallanzani collection. Secured within an anonymous wooden box, the presence of an Egyptian mummy in Pavia was forgotten until recent times, when it was rediscovered and soon transferred to the now Museo di Archeologia dell'Università di Pavia, directed by Professor Maurizio Harari.

Spazio Geco, in partnership with the Mummy Project Research, directed by Sabina Malgora, and the IRCCS Policlinico San Matteo Foundation, proposed a project aimed at studying, preserving, and enhancing the mummy (Belvedere et al. 2022b; Sabina 2017). The extensive analysis involved using computed tomography and radiocarbon techniques implemented by San Matteo Hospital in Pavia. These data allowed the researchers to draw up the mummy's anthropological profile: She is a female of roughly twenty to twenty-two years old, who lived in the third century B.C., and had given birth at least once in her lifetime (workflow stage: acquisition). See Figure 1.

Figure 1. Flow process of the project, the Mummy

(A) The original mummy; (B) the mummy scanned CT (workflow stage: acquisition); (C) the digital model of the mummy (workflow stage: modelization); (D) the sliced reproduced replica (workflow stages: prototyping and realization).
Source: Spazio Geco.

Afterwards, the mummy was musealized and reinterpreted. The "Egyptian Corner," a permanent exhibit inside the archeological museum, was launched in 2017 and includes the display of the mummy within a showcase as well as a full-size tactile reproduction. The data gathered by previous analysis were used to reconstruct the digital model (modelization). Experts including engineers and designers decided to re-prototype the mummy as a wooden model made from numerous slices manufactured by CNC machines (prototyping and realization). The "slicing technique"

overcomes the spatial limitation of the machine (2500 x 1300 x 200 mm, single-direction drilling).

The replica is now both visible and touchable, displayed in the original wooden box in which the original mummy had been kept for so many years as a way to highlight its history and its arrival to Pavia. The inside of the lid displays a message two centuries old: "Mummia egiziana di una donna morta 810 anni prima dell'era volgare. Dono di S. Giorgiani del Cairo del 1824" ("Egyptian mummy of a woman who died 810 years before the Common Era. Gift from S. Giorgiani from Cairo in 1824" (translation by the authors)).

The Egyptian Corner since its launch has been welcoming visitors, including children, foreigners, and people with disabilities. The project has democratized the conservation and exhibition process. It also has achieved "design for all" objectives, because the mummy now has become highly accessible by various communities.

Table 2. General information of the project, the Wunderkammer 4.0

The Wunderkammer 4.0

Project	Wunderkammer 4.0
Year	2022
Client	Museo Civico e Gipsoteca Bistolfi, Casale Monferrato (province of Alba), Italy
Goal	Accessibility, interactivity, and participatory
Scientific partnership	Sabina Malgora

The collaboration between Spazio Geco and Sabina Malgora's Mummy Project Research led to another project: the Wunderkammer 4.0. The Museo Civico e Gipsoteca Bistolfi expressed the desire to enhance the collection of Carlo Vidua, an explorer, and collector from Casale Monferrato who lived between the eighteenth and the nineteenth centuries and left to his hometown treasures and curiosities from all over the world. His Egyptian collection, in particular, faced problems: The artifacts are distributed partly in the Civic Museum of Casale Monferrato and partly at the Egypt Museum of Turin. Furthermore, the exhibit in Casale Monferrato is located in the underground room, making it unavailable to motor-disabled people.

The aim of the project, therefore, was to unite the pieces from the Vidua's collection and make them accessible and interactive to everyone. It was proposed to recreate – at least ideally – the typical eighteenth and

nineteenth-century cabinet of curiosities: the Wunderkammer, the "wonder chamber." Once selected, the most distinctive objects in the collection were scanned to remodel in 3D, which were then printed and hand-painted. These 3D replicas were fitted with RFID tags: Once placed on the reader, each artifact narrates its own story through a video on a monitor. This permanent exhibit not only allows people with mobility issues or those with visual disabilities to enjoy part of Vidua's collection but also offers an occasion of gamification within the museum: Indeed, the statuettes may be used during laboratories and seminars as pawns of board games or within other activities. In this sense, two goals of museum design have been achieved, human-centric design and experience enhancement.

Figure 2. Flow process of the project, "The Wunderkammer 4.0"

(A) Scanning artifacts (workflow stage: acquisition); (B) remodel acquisition on computer (workflow stage: modelization); (C) printing models and (D) manufacturing the structure (workflow stages: prototyping and realization).
Source: Spazio Geco.

Table 3. General information of the project, Belgioioso Castle

Belgioioso Castle

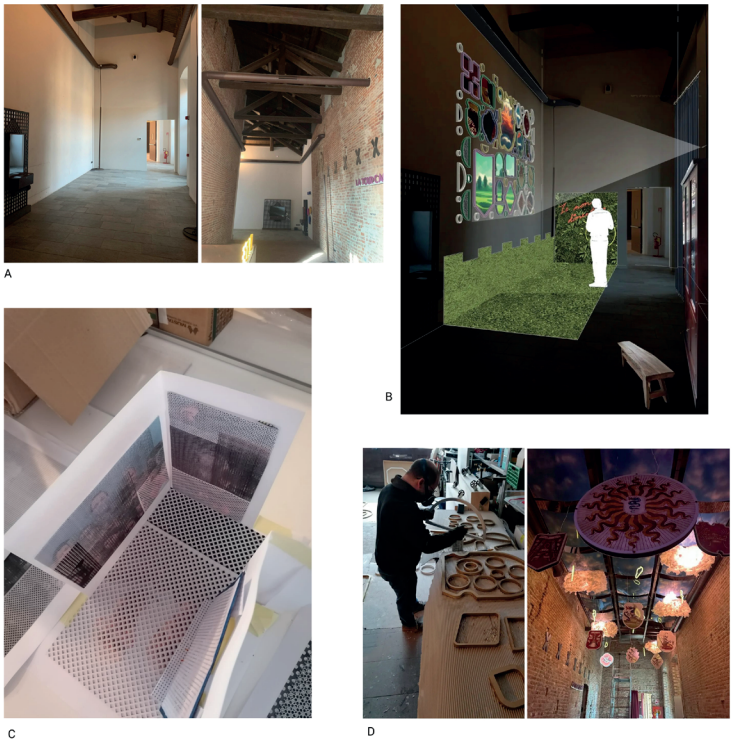
Project	Project: Il Museo dei Visconti
Year	From 2019
Client	Comune di Belgioioso (province of Pavia), Italy
Goal	Accessibility and interactivity
Scientific partnership	-

Belgioioso Castle is a historical building located in a town a few kilometers from Pavia. The main problem of this "museum" is the lack of original antiquities. To resolve this problem, Spazio Geco has been invited to revitalize the internal spaces of the castle.

A series of permanent installations seeks to transform the rooms of the medieval section of the castle into an immersive and interactive museum dedicated to the Visconti family. Spazio Geco made a careful analysis of historical sources, content ideation, experience design, hardware programming, and production of supports and scenic so as to offer the public a unique, immersive experience. DF play an important role in this case, as materials and memories are abstractly digitized then fabricated with a modern esthetic.

"Le Jardin" is an example of the transformation. Here, wooden frames were manufactured, installed on the wall above an artificial grass lawn, then video-mapped with overlays of important figures and pictures to evoke the atmosphere of a royal court garden. In this way, visitors can immerse themselves in the pleasures of the Visconti family. On the other hand, "Nel Cielo in Tempesta" (Under the Stormy Sky), visitors will pass through an environment that recreates a violent storm. Yet visitors do not see lightning and rain descending from the clouds but rather symbols and emblems related to the Visconti family. From artificial clouds made from cotton, lightning in LED strips, amplifying the effects of a stormy and leaden sky, symbols and emblems were illuminated and hung that refer to the power of the family. In this case, digital manufacture does not replicate the exact original artifacts but evokes memory, feelings, and an atmosphere in the exhibition. The lost memories were then recalled by an interesting method of mixed media, as well as immersive storytelling techniques. The experience inside the museum no longer has to depend on the existence of original antiquities but on the sequence of encounters visitors passed through.

Figure 3. Flow process of the project, "Belgioioso Castle"



(A) Site survey (workflow stage: acquisition); (B) spatial conception and (C) proposition simulation (workflow stages: modelization and prototyping); (D) manufacture and installation on site (workflow stage: realization)
Source: Spazio Geco.

Conclusion and Discussion

Table 4. Works involved and comparison of effects among three projects

N.	Cases	Activities involved	Value enhancement
1	The mummy	Antiquities reconstruction	Accessibility, inclusivity
2	The Wunderkammer 4.0	Antiquities reconstruction and interactive device construction	Accessibility, inclusivity, and interactivity
3	The Belgioioso Castle	Spatial interactive exhibition	Accessibility, interactivity, narrativity

It is worth noting that among the three projects, the use of DF in museum design for CH enhancement varies. In the first case, the aim of DF is to simulate and to exhibit the exact artifact with the same scale for better preservation as well as educational support. The mummy has been represented by slices, broadening other visitors' point of view as to the detail of each section on the whole body. The Wunderkammer 4.0 transformed the original museum model from a "no touch" to "please touch" experience by inviting visitors to interact with artifacts. This choice resolved the problem of artifact scatter. Yet the solution also proposed a new concept for the classic definition of the "cabinet of curiosities," which has the potential to showcase the greater collection by highlighting parts of it. Therefore the project accomplished human-centered and museum experience enhancement design. In the project of the Belgioioso Castle, DF acts as an efficient tool in materializing the "atmosphere" of the Visconti period. The project remade almost empty rooms into a series of storytelling experiences, not by text alone but interactive and immersive technology. DF was used flexibly in this case not only as the toolset for artifact reproduction but also as a scenographic technique. The application of the four-step workflow in three tales also proves that the same procedure can execute diverse results depending on the context and the objectives of each project.

The cases mentioned in this project are empirical, meaning that the use of DF is constrained by many factors. That there still remain limitations on the potential of DF in museum design for CH purposes is worth noticing, because it may lead to various other scales and project types. The question at this point is no longer if DF can be useful for CH projects, so much as how DF can be developed vary its use in different contexts and for differing aims. The development of museology currently has broken

through limitations of interior, or architectural scale, to even larger scales, particularly urban or landscape (open-air museums, ecomuseum, natural reserve, cultural itinerary), with more complex requirements of diverse kinds of intervention, narrative structures, disciplines, accessibility/inclusivity, scenographic experiences, collections, and their interpretation.

To be integrated, DF techniques have to be developed, upgraded, and calibrated to adapt in the new environments. Furthermore, the museum experience also has to be updated by fashion, so that the content inside the museum does not become obsolete. In the future, there is also an urgent need to delve into new forms and new technologies for DF, which will lead to new workflows. Within the limitation of the projects, tools, and people, our research opens new perspectives on applying DF on CH projects.

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