The Conservation of Cultural Heritage in Conditions of Risk, with 3D Printing on the Architectural Scale

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Abstract. Nowadays we are witnessing several demonstrations of damage, destruction, and loss of collective Heritage. Among these, according to the UNESCO *List of World Heritage in Danger*, we can mention ongoing conflicts around the world, environmental issues due to natural disruptions, and substantial vandalism.

Therefore, effective response capability and quick turn out applications are required in order to satisfy the current and future demand for environmental, social and economic sustainability.

The latest building site automation systems and 3D printing technologies (rapid prototyping) represent an applied experimentation of the effective realisation of three-dimensional volumes at different scales, from the design object to the building component, obtained by processing digital data with appropriate software.

Indeed, the coordination of specific tools for the three-dimensional survey, digital modelling, and additive manufacturing now eases the production of components or architectural components, aiming to elaborate new constructive settings that will contribute to update the modalities of management, conservation, and use of the Cultural Heritage.

At an international level, significant case studies bear testimony to how 3D printers allow the construction of free-forms structures or conventional multi-level buildings, by using the most common additive implementation systems, namely: powder bed deposition and cold extrusion layering.

The refining of these technologies can offer a useful contribution to building site security management, reconstruction time rate, interventions cost, and innovative design, within Heritage restoration and conservation frameworks.

Keywords: Cultural Heritage · 3D printing · Reconstruction

1 Introduction

1.1 Scientific Background

The current lack of innovation within the building process highlights the need to identify new methodologies in order to enhance established construction procedures, which

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innovative characteristics are often the result of technological transfers from other applications, including naval and aeronautical engineering. Researchers are now attempting to demonstrate the applicability of automation technologies in architecture and aiming to industrialise the building process, not so much as a standardisation of the outputs but as the modernisation of each stage of execution, taking into account culturally rooted craftsmanship [1]. As a result, a simplified organisation on the building site, a crosscheck of planned phases, a replicability of process under different circumstances, and a reliability of outcome (standard elements or unique pieces) over time are expected.

Today, some typical aspects of prefabrication in building construction refer to materials and components that are executed off-site under controlled environmental conditions, to ensure high quality and certified performance. The advancement of the research, however, is deepening on-site automation procedures to increase the effectiveness of operations on the building site. Among the most advanced systems, we can mention valuable examples such as software-guided cranes for soil moving [2], robotic arms to install building elements [3], flying robots to displace and position construction materials [4], and large-scale 3D printers to create architectural components [5].

The application of the aforementioned innovations is worthwhile in contexts of emergency which require high-quality interventions, appropriate costs/benefit balances, and short reconstruction times, for example after landslides and earthquakes, and during armed conflicts. 3D printing [6], a technology with low operating costs and little material waste, for instance, has already been tested for the production of temporary housing modules to be used in post-emergency situations (*Unacasatuttadunpezzo*, by *Dshape* Company [7], *Technological Village*, by *Wasproject* [8]). It falls into the category of additive systems, which create volumes by adding overlapping layers of apposite printable materials, instead of subtracting portions from an initial compact volume - the usual procedure in industrial production.

The ability to change material *case-by-case,* depending on the circumstances and the result sought (required dimensions or load-bearing properties), has opened the possibility of using additive manufacturing for interventions on existing buildings, that may include volumetric additions or new insertions to fill envelopes or wall gaps (see Fig. 1).

At an international level, the collective Cultural Heritage is subject to risk events, from environmental, social or political turmoil. These occurrences may produce different damage at different scales, from objects of high historical value to architectural constructions, and to entire urban fabrics. Specifically, the phenomena of danger that affect buildings implicate a set of difficulties to be faced during the restoration procedures, which may include structural deficiencies, deterioration of the external envelope, and the absence of volumetric unity. The present study was undertaken with the purpose of analysing these criticalities and addressing a possible intervention methodology where reconstruction works are required, supported by technological progress.

In 1972, in the frame of the *World Heritage Convention,* the UNESCO defined a *List of World Heritage in Danger* [9], to keep track of ongoing worldwide risk episodes facing the world's Cultural Heritage. Following precise criteria (such as imminent or potential danger, based on social-political and environmental stability), and constantly updated over the years, the *List* "informs the international community of conditions which threaten the very characteristics for which a property was inscribed on the *World*

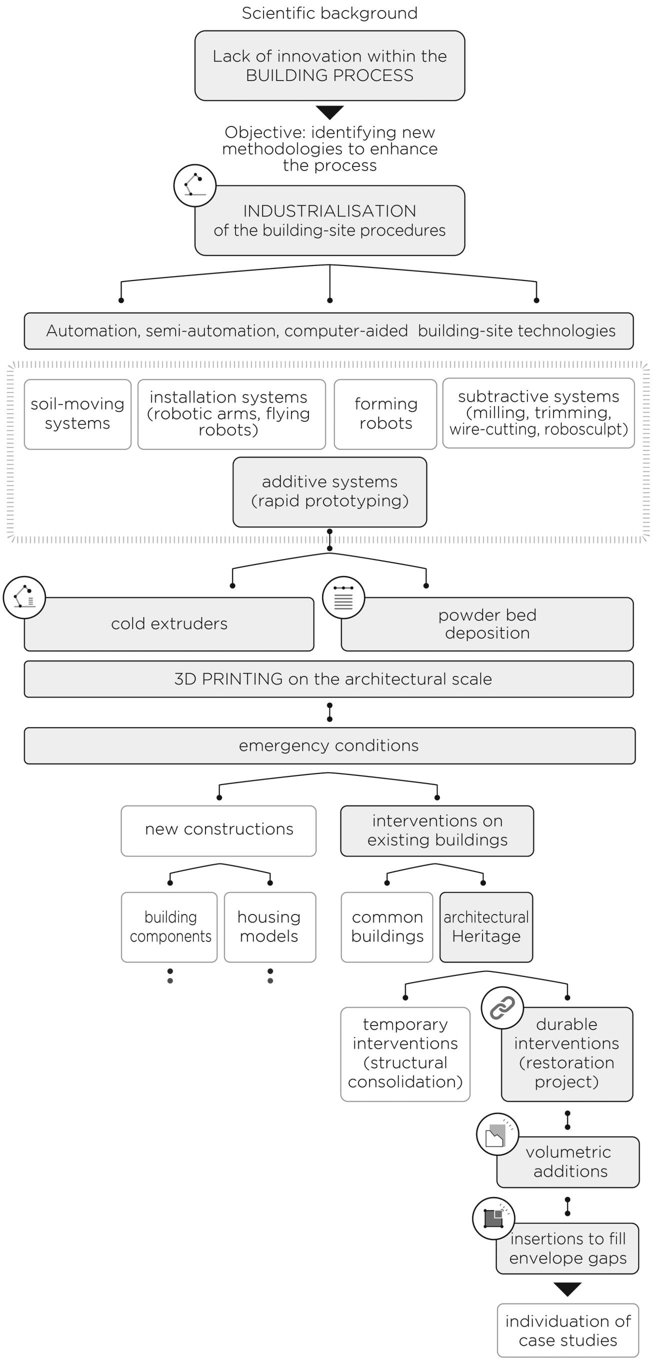

Fig. 1. Diagram summarising the individuation process of the subject under study (scheme edited by Sara Codarin).

Heritage List and in order to encourage corrective action". For this reason, the committee has drawn up a sequence of articles to clarify in which terms a property can be included among the under-protection resources and the respective procedures to be followed. According to the Art. 11 of the *Convention*, "the list may include only such property forming part of the cultural and natural Heritage as is threatened by disappearance caused by accelerated deterioration; (…) abandonment for any reason whatsoever; the outbreak or the threat of an armed conflict. Calamities and cataclysms; serious fires, earthquakes, landslides; volcanic eruptions; changes in water level, floods, and tidal waves".

Currently, the database includes 54 sites - 38 cultural and 16 natural - located worldwide. Among them, we can find historical centres, architectural buildings, and archaeological excavations. The impending risks identified for each location may cause punctual or diffuse damage, along with partial loss of volume or total destruction. Recovery must make use of conservation procedures designed to preserve the historical good for future generations and restore the formal unity of the work with appropriate reconstruction operations [10].

Thus the potential of large-scale 3D printing, in light of its compatibility with experimental performative materials and its ability to generate customised volumes with no geometric constraints, suggests the elaboration of a new construction methodology for restoration that takes sustainability into account.

The development of this technology could adapt effectively to different design requirements, with the possibility of achieving comparable results to those obtainable through traditional processes.

2 Innovative Intervention on CH and Cultural Background

2.1 The Role of Technological Advancement Within the Charters of Restoration

The development of new construction technologies opens a debate on the legitimacy of their application for restoration projects on the Architectural Heritage. Technical advancements in construction was a topic discussed during the elaboration of the Charters of Restoration, which was established in the twentieth century to support the development of the discipline.

In 1931, during the *First International Congress of Architects and Technicians of Historic Monuments,* the drafting of the *Athens Charter* laid down the basic principles for the conservation of Architectural Heritage [11]. Ever since, from a technical point of view, philological restoration was preferred to stylistic interventions (art. II) and the use of modern materials such as reinforced concrete for consolidation was admitted (art. V). However, anastylosis - the replacement of dismembered parts with a minimal amount of neutral elements to represent the image in its integrity and ensure its preservation - was the only proposed option for archaeological restoration (art. IV).

Conversely, the *Italian Restoration Charter* - the first official Italian guideline in this field - adopted in 1932 [12] showed a greater openness towards using the latest technologies for scientific restoration (art. 2). However, the Charter remained unmovable on the subject of anastylosis, as it viewed archaeological ruins as too remote from our traditions and our present civilisation (art. 3).

This concept is also expressed in the *Venice Charter* of 1964 [13], a post-war document where the concepts of tangible and intangible Heritage were introduced. Article 15 states: "all reconstruction work should, however, be ruled out *a priori*. Only anastylosis (…) can be permitted. The material used for integration should always be recognisable and its use should be the least that will ensure the conservation of a monument and the reinstatement of its form". The international committee, which gave the text a non-Eurocentric character, determined technical aspects as contributors to post-intervention recognisability for conservation purposes, and emphasised the idea that "the process of restoration must stop at the point where conjecture begins" (art. 9).

The terminology expressed up to this point, especially with regard to the possible modernisation of reconstruction processes in any work of art - pictorial, sculptural or architectural - was further refined in the *Italian Restoration Charter* of 1972 [14], issued as a circular by the Ministry of the Public Education. Given the cultural context of that time, the Charter of 1972 effectively prevented any "stylistic or analogical completions even in simplified forms, demolitions erasing the past, and patina removals" (art. 6). Instead, for the reintegration of small parts, "the reparation of properties that have volumetric gaps should be conducted with techniques and neutral materials that can be easily recognisable and without inserting crucial elements that may influence the figurative image of the object" (art. 7). The Charter accepted the use of new procedures and innovative materials - preferably already tested - for restoration works on Architectural Heritage, but only if minimised in comparison with the volume of pre-existence (art. 9).

Later, the *Declaration of Amsterdam* of 1975 [15], adopted by the Ministers Committee of the European Council only three years after the UNESCO *List of World Heritage in Danger* was drafted, took into account the risk conditions that specifically threaten the European Cultural Heritage, and represented a partial step back in conservation theories. A central paragraph of the manuscript states: "steps should be taken to ensure that traditional building materials remain available and that traditional crafts and techniques continue to be used. (…) Every rehabilitation scheme should be studied thoroughly before it is carried out. (…) New materials and techniques should be used only after approval by independent scientific institutions".

The official papers written in the following years provide an in-depth exploration of methods for recovering historical urban centres (the *Washington Charter on the Conservation of Historic Towns and Urban Areas* of 1987 [16]), archaeological sites (*Lausanne Charter for the Protection and Management of the Archaeological Heritage* of 1990 [17]), and built Heritage and landscape (Cracow Charter of 2000 [18]).

In 2003, the *ICOMOS 14th General Assembly* in Zimbabwe produced a document of international relevance: the *ICOMOS Charter, Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage* [19]. A synthesis of the principles previously outlined, the document favours an openness towards new constructive technologies, as long as they are consistent and compatible with pre-existing conditions. Article 3 is particularly important because it proposes detailed guidelines for Heritage restoration, remedial measures, and proper supervision of projects. First, "the choice between *traditional* and *innovative* techniques should be weighed up on a *case-by-case* basis and the preference is given to those that are least invasive and most compatible with Heritage values, bearing in mind safety and durability requirements" (art. 3.7).

Moreover, "where possible, any measures adopted should be reversible so that they can be removed and replaced with more suitable measures when new knowledge is acquired. Where they are not completely reversible, interventions should not limit further interventions" (art. 3.9). The characteristics of these techniques, especially new ones, "used in restoration and their compatibility with existing materials should be fully established. This must include long-term impacts so that the undesirable side-effects are avoided" (art. 3.10). Finally, bearing in mind the concept of cultural consistency, "each intervention should, as far as possible, respect the concept, techniques and historical value of the original or earlier states of the structure and leaves evidence that can be recognised in the future" (art. 3.12).

In this regard, we can assume that the Charters drafted at the beginning of the century postulated the basic principles of restoration and addressed the discipline mainly for conservative purposes; this is particularly evident if we consider that the committees members were solely European. On the other hand, recent Charters are better disposed toward the use of new technologies - even experimental - within the construction industry.

New technologies do not only represent an ordinary improvement to existing restoration methods; rather, they are substantially upgrading the traditional construction processes when they can meet the Charters requirements.

The verifiability of additive manufacturing leads us to imagine the effects of using 3D printing in the field of Heritage conservation. As will be explained in the next section, these manufacturing systems are adaptable in terms of printable materials, processing techniques, and installation modality of the outcomes. Indeed, they inspire discussion and debate about the consistency of applying experimental techniques that are different from the processes that led to the construction of the historical building. In fact, these techniques are more easily accepted for volumetric additions as independent objects that can be treated discontinuously with the existing, rather than for restoration interventions.

Given that 3D printing takes advantage of constructive principles derived from the past and reinterprets the traditional realisation and installation methodologies, it can then be used to produce construction elements - loading bearing or not - in order to fill gaps in damaged envelopes or structures. To support this concept, we present references to various case studies, taking into account different scenarios in which architectural reconstructions or volumetric integrations are required. The selected examples (buildings that are already damaged or under risk conditions) will be useful to compare *case-by-case* the proposed interventions using additive manufacturing with the methodologies outlined in the restoration theories, and then verify that the application of these technologies ensures compliance with the parameters set out in the Charters.

3 3D Printing Systems: Advantages, Limitations, and Potentials

3.1 State of the Art of Large-Scale Additive Manufacturing

The architectural design on pre-existent buildings requires high precision. The improvement of digital survey processes, three-dimensional modelling, and data management has addressed, for this purpose, the experimentation of computer-guided machines programmed to handle, install and assemble construction components [20]. Among the building site automation technologies (see Fig. 2), 3D printing systems (developed over the last few decades to optimise the design of prototypes within the industrial production chains and recently applied on the building scale) open scenarios for a possible application in the framework of existing building design. Unlike the subtractive technologies, which are commonly used for the production of design objects or technical components, 3D printing (also called rapid prototyping for its qualities to create results in a short time) allows the realisation of complex volumes through an additive processing. The printer mechanism provides the overlapping of consecutive thin layers of printable material (formulated to solidify instantly and support structural loads) with minimal material waste [21].

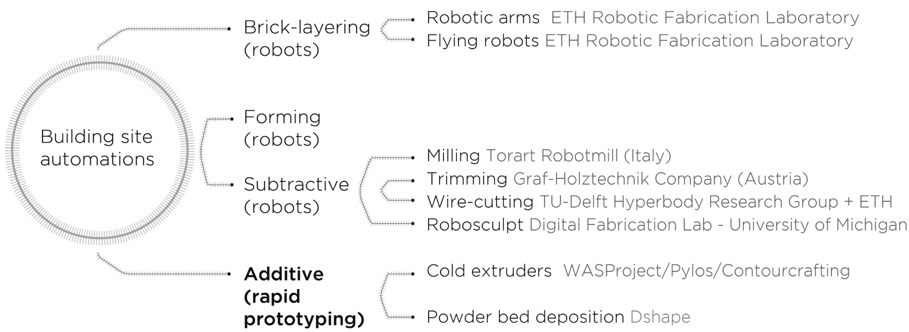

Fig. 2. Diagram of the most recent building site automation systems. 3D printing is an additive construction technology (scheme edited by Sara Codarin).

3D printed objects (previously digitally modelled) can be monolithic elements or plural objects (to be carried and placed on-site, after a possible pre-assembling phase

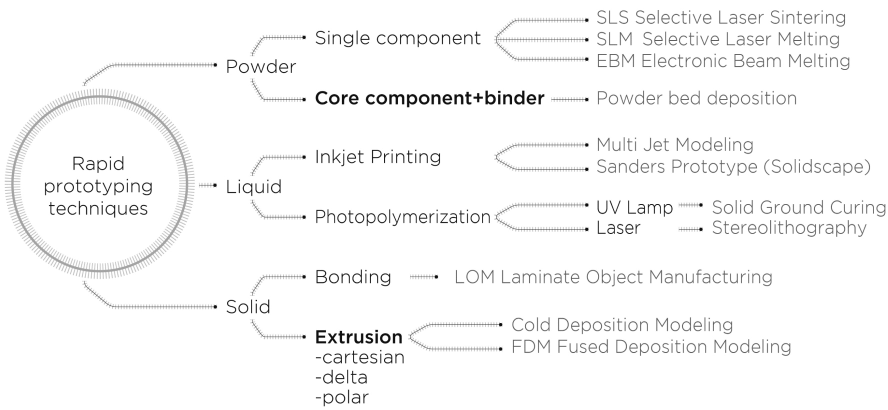

Fig. 3. Classification of the 3D printing techniques, based on materials processing. Currently, the construction industry is experimenting powder bed deposition and cold extrusion to print building elements (scheme edited by Sara Codarin).

off-site) composed of a homogeneous material that can be sand, plaster, clay or cement based. The most widespread innovative techniques (see Fig. 3) suitable for large-scale applications are machines that work by powder bed deposition processing or by cold extrusion.

Powder bed deposition works by layering on the printing area alternatively a base material (generally sand or gypsum) and an inorganic binder (see Fig. 4). This technique allows obtaining free-form monolithic shapes with no geometric limitations on any axis.

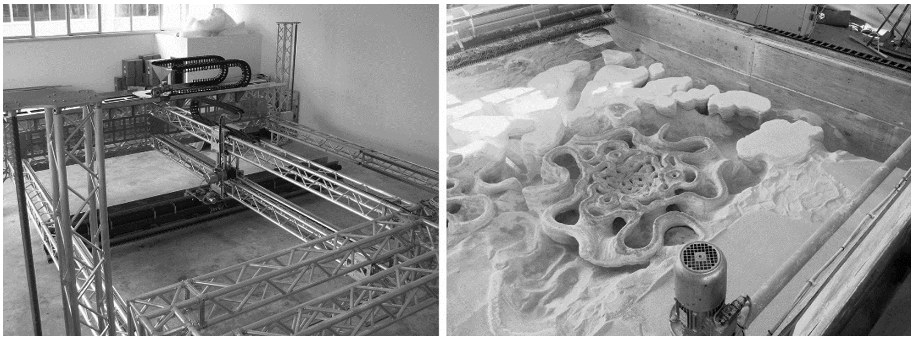

Fig. 4. Powder bed deposition 3D printer that allows the creation of free-form volumes. It consists of a sequence of nozzles that translate along the Cartesian area depositing sand and consequently the binder in all zones that are to be solidified. At the end of the process, the exceeding material is aspirated from the cavities in order to be reused (courtesy of *Dshape*).

The cold extrusion 3D printing technology consists of three arms connected to one point and moving in any direction (see Fig. 5). In this case, 3D printers are equipped with an extruder designed to deposit overlapping layers of a viscous mixture (commonly, based on raw soil or concrete conglomerates) able to solidify in a short time [22].

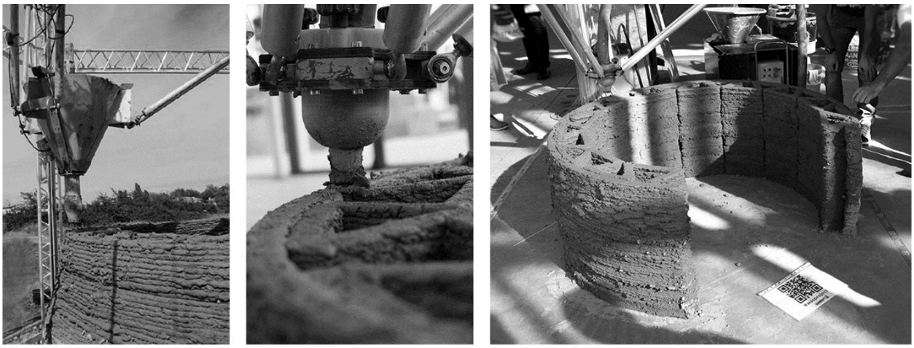

Fig. 5. 3D printers composed by an extruder programmed to deposit overlapping layers of a mixture that solidifies instantly (courtesy of *Wasproject*).

3.2 Reasons for Using Additive Manufacturing

Economic sustainability and innovation. Over the last decades, 3D printing has played a key role within the development of circular business models [23]: rapid prototyping can be an effective tool to extend the life of products (repairing not standard-shaped items that are already out of production) and to reduce resources consumption (recovery of waste materials in new printing mixtures). Recent research has also highlighted the economic and environmental potential of this technology also for large-scale constructions in terms of topological optimization, cost containment, and environmental impact reduction [24].

The prevailing cost component is the initial investment for the acquisition of the machine. Then, the production expense relates only to the value of the printable material, although nowadays it is relatively expensive. As a consequence, unlike the industrial production, the price of each produced element does not decrease depending on the quantity, but it does not increase based on its complexity or scale (part, component, module, or unit) [25].

3D printing allows working on-site, off-site and near the construction site, with the advantage of efficiently managing construction sequences (it avoids on-site storage of construction material that happens when the different construction phases are not well coordinated because of technical delays) without installing scaffolding or wet casting cartridges. Experts agree that this technology is not mature yet, as some aspect are still not controllable. Nevertheless, we can anticipate how it could be used once optimised, according to future regulations, and made accessible for architectural constructions.

Rapid prototyping - along with subtractive, moving, forming, and installing building site automations - represents an innovation that, in the coming years, could support or even substitute traditional construction tools [26]. This technological upgrading trend can be seen in *Foster's curve of innovation* of 1986 on the development and replacement of technologies according to the time variation (see Fig. 6).

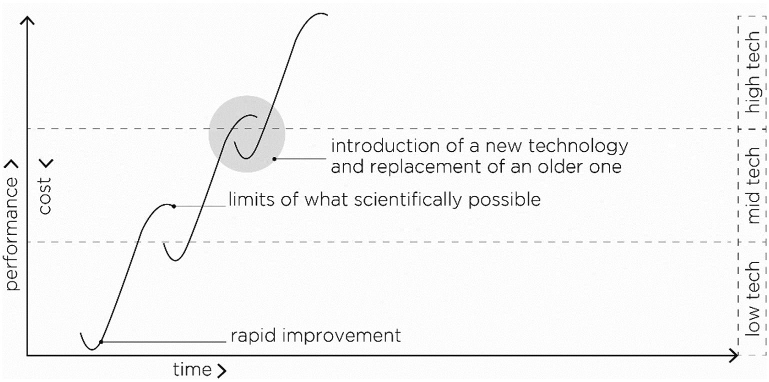

Fig. 6. *Foster's curve of innovation* showing that when a technology reaches its mature stage, it becomes increasingly vulnerable to substitute technologies (image edited by Sara Codarin).

Application potentials on existing buildings. Large-scale 3D printed objects can be used to fill wall gaps caused, for instance, by natural disasters, insufficient maintenance, or armed conflicts, in order to enhance reconstruction procedures in emergency situations. This methodology could help securing building structures hit by earthquakes, solving wall cracks that let the atmospheric agents enter the construction, and adding new components or entire structural systems essential for the future reuse of buildings.

The additions, which could be realised by a mechanical arm designed to deposit material (replacing workers in dangerous areas), can be punctual elements, new entire walls or new volumes inserted in the original historical envelope. The production of components matching perfectly with the gaps is possible by using as a starting point a digital survey (specifically performed to allow the recovery operation) and then taking into consideration the geometric tolerances. Both for structural and non-structural interventions, the printable material (raw soil, conglomerates, sand) has to be physically and chemically compatible with the historical building (generally made of brick, wood or stone) under study. In case of catastrophic events, the use of recovery materials obtained by grinding rubble could be an option: the rubble collected from damaged buildings, for example, could influence positively the cost of material transportation (especially when emergency areas are not accessible and the construction resources cannot be found locally). The definition of this process involves the analysis of further aspects such as the cost for moving the grinding machines and the difficulty of rapidly generating a printable homogeneous material.

Structural performances. A missing part of an architectural envelope can be replaced by a 3D printed component realised, as an example, on-site with a mechanical arm programmed to extrude a quick hardening mixture. After an earthquake or a disaster, for instance, an arch keystone may not be right-sized to be repositioned (following the anastylosis principles) and therefore achieve again the load-bearing capacity. So, if a new piece with a different shape has to be printed in substitution, before any intervention, all gaps and broken elements should be surveyed. The integration should not create a negative influence on the pre-existence (mainly on the interface between the new insertion and the original building system) or modify stiffness and ductility levels. If it is too soft, its mechanical features come into play only when the structure undergoes irreparable deformations. Conversely, if too rigid, it might crack even before the structure does. A load-bearing 3D printed element should not be weaker or stronger than the existing system. Instead, ported structures (such as a cornice or a curtain wall) can be lightened by using alveolar masses and therefore improving the mechanical reaction to seismic events.

The more advanced 3D printing processes can realise each three-dimensional point (*voxel*) with different mechanical characteristics. However, resistance tests are strictly necessary in order to decide whether the printing process, to achieve reliable results, should take place in a protected environment (off-site) or directly on-site.

Accuracy of the results. The choice of the language to be achieved within a conservative recovery process is essential to decide the most appropriate tool (machine and material) to be used. *Case-by-case*, it is necessary to understand how to face the reconstruction of missing parts. It is possible by imitating the original elements or making them fully identifiable. The first strategy works with inert, binder and additives materials that favour the integration of the reconstructed part, which is recognisable only through an expert and close analysis. The second approach aims at providing an integration with the original portions, but at the same time, it excludes the complete mimesis. The resulting readability of the figurative image can be compared (in this case at the three-dimensional and not coplanar level) with the pictorial integration techniques as the *tracing* method [27], or the chromatic abstraction/selection technique consisting of the application of uniform tonal macro-spots on damaged surfaces. We can chose such options for conservative integrations or new envelope additions (when new insertions are clearly different from the original building system).

Through 3D printing, indeed, it is possible to elaborate organic shaped geometries (to be managed by using digital software) in order to express a duality through an evident differentiation of volumes.

Contemporary approach. Interventions on existing buildings, that means on a given context, through innovative techniques and materials, transfer a message of ongoing cultural transformation and declare today's historical era, "according to criteria that regulate new renovation constructions such as minimum intervention, reversibility, and expressive distinctiveness". In particular, new materials are defined to optimise the performance of each prototyped components and thus to take advantage of the maximum of their static and figurative possibilities. Therefore, new scenarios and innovative design paradigms can be foreseen [28].

4 Possibility of Use for CH Conservation and Methodology

Technical procedures. In this section, we want to propose an innovative intervention programming on Cultural Heritage, using 3D printers and experimental materials [29]. Preventively, a database of three-dimensional models obtained possibly by a precautionary non-invasive survey should be provided. Moreover, given the lack of significant 3D printing realisations on the architectural scale (that means not only sculptural, pictorial or decorative apparatuses) in the field of restoration, this procedure ought to be justified by the elaboration of a pilot case which foresees:

- a choice of the most appropriate 3D printing technology on the basis of the size and morphology of the building lack;
- processing of a three-dimensional model, in order to select and elaborate the building damaged component, with minimal waste of resources, as long as the procedure consists of additive rapid prototyping;
- individuation of an eligible printable material which could be selected from a database of certified and compatible mixtures;
- on-site definition of a 3D printed reversible matrix to recreate the missing part of the architectural system. It could ensure structural performances and improved responsiveness to seismic stresses, thanks to the possibility to manage specifically material mass, density, and weight with a fast realisation timing;

- delineation of a specific interface area with possible punctual connections to merge the existing building to the reconstructed component.

Damaged construction parts can be realised either on-site by using the cold extrusion technology or off-site (eventually near the construction site) with a powder bed deposition 3D printer.

In the first case, mechanical arms on a truss cage can be used to consolidate the gap and to avoid further collapses. A printer with a mechanical arm, lifted at a specific level, working with quick-drying and rapid hardening material can be used for this kind of intervention. Oscillations, overhead works of the mechanical arm, and positioning of the nozzles have to be precisely controlled. Quick-drying and rapid hardening materials once extruded are able, in a very short time, to reach a sufficient load bearing capacities to support the following extrusions. To increase the adhesion of the mixture to the masonry, the extruder could also remove dust and non-coherent materials through a washing procedure or air blowing.

The use of powder bed deposition, instead, is preferable off-site or near the construction site, but the procedure can also be applied for on-site prefabrication.

Comparison with the constructive tradition. 3D printing on the architectural scale has revolutionised the hitherto construction rules but at the same time allows defining design intervention by taking into account the cultural background of each historical building. It can improve the quality of the whole process, especially with regard to the realisation of tailored building elements, with a reduced margin of constructive error that often occur in constrained or emergency conditions.

The outcomes of rapid prototyping procedures (technical details), if designed with accuracy, are compatible with the pre-existence from the structural and the formal point of view (volumetric completeness and chromatic similarity). The same result is achievable through traditional or innovative (additive production) systems, in compliance with the Charters requirements. A checklist of fundamental key points extracted from the Charters should be used to verify the legitimacy of 3D printed projects, in contexts where reconstruction is needed and where the monuments state of degradation does not allow the anastylosis. It may be considered:

- minimum intervention (1931 *Athens Charter*, 1932 *Italian Charter*, 1964 *Venice Charter*, 1972 *Italian Charter*, 2000 *Cracow Charter,* 2003 *ICOMOS Charter*);
- intervention reversibility (1972 *Italian Charter*, 2000 *Cracow Charter*, 2003 *ICOMOS Charter*);
- compatibility of the new integration (1972 *Italian Charter*, 2000 *Cracow Charter*, 2003 *ICOMOS Charter*);
- recognisability of the new insertion (1931 *Athens Charter*, 1972 *Italian Charter*, 1964 *Venice Charter*, 1972 *Italian Charter*, 2003 *ICOMOS Charter*);
- readability of the formal unity (1931 *Athens Charter*, 1972 *Italian Charter*, 2003 *ICOMOS Charter*);
- case-by-case approach (1931 *Athens Charter*, 1932 *Italian Charter*, 1972 *Italian Charter*, 2003 *ICOMOS Charter*);

– use of modern materials and construction techniques (1972 *Italian Charter*, 2003 *ICOMOS Charter*).

5 Intervention Scenarios and Cases Study

Recalling the article 11 of the *World Heritage Convention* of the 1972, as references for possible future scenarios we can use examples of Cultural Heritage at risk because of "outbreak or threat of an armed conflict", "calamities and cataclysms occurrences", and "accelerated deterioration" caused by the lack of maintenance on buildings.

This framing will be the starting point to propose innovative restoration interventions through the realisation processes so far described.

5.1 Outbreak or Threat of an Armed Conflict

Historical architectures, monuments, or archaeological excavations are not always accessible in contexts subjected for short or long periods to political or social tensions.

Under these circumstances, it is not possible to keep controlled the status of the constructions or to intervene immediately in case of damage or destructions. Therefore, because of the inability to visit the original architectural work, the primary objective should be the attempt to transfer its formal unity and, above all, its symbolic value (even though extrapolated from the historical and environmental context in which the work is located) in order to transfer its cultural importance. Any divulgation of information about historical buildings that are being destroyed or damaged by armed conflicts can be a key point to promote the collection of data (photos, 3D models obtained by digital surveys of photogrammetry technique) that will be fundamental to accelerate post-emergency construction or securing interventions. Nevertheless, database creation should always be a preventive procedure, especially in areas where conflicts are expected to happen.

The archaeological site of Palmyra, which is included in the UNESCO *List of World Heritage in Danger*, has suffered irreversible damages after recent conflictual events. Researchers from the Oxford University in collaboration with the *Institute of Digital Archaeology* [30], through an information campaign, has collected a large number of photographs of the site taken in different periods, that helped creating a three-dimensional model of all monuments of the location. Afterwards, they decided to create a scaled-down copy of the Arch of Palmyra as a symbolic element of the whole site, to diffuse its cultural message and keep promoting data documentation (see Fig. 7).

The prototype, realised by *Dshape* and *Torart* Companies, was obtained by adopting a numerical controlled subtractive technology on marble blocks, guided by a digital model input, obtained through photogrammetric technique. However, in a second phase, the procedure could be optimised using additive processes: the printers could be installed directly at the intervention areas with the objective of employing local resources (e.g. sand or ground soil) for the definition of 3D printable mixtures (after analysing the mechanical properties on material samples), to obtain an effective integration with the context. The configuration of the site is compatible with the application of on-site cold extrusion or off-site powder bed deposition.

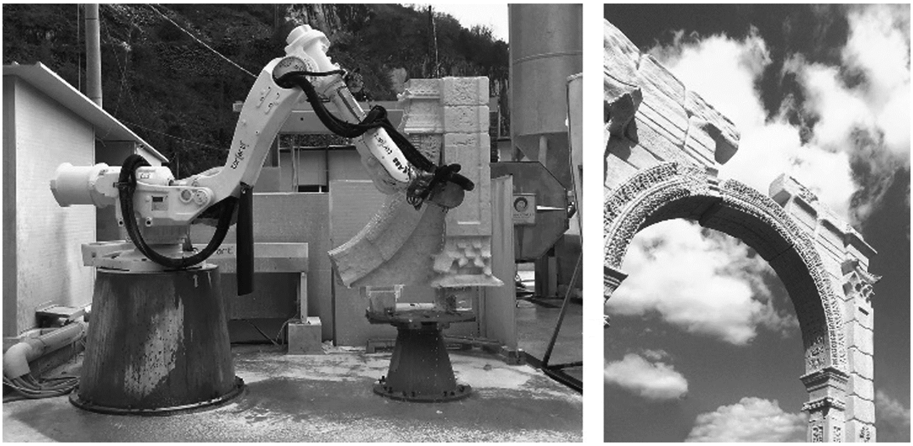

Fig. 7. The realisation of Palmyra's arch through subtractive processing (courtesy of by *Dshape*) and the final three-dimensional model (photo by Sara Codarin).

The language used for the new added components can be expressed in pure forms or with decorative design hints (depending on the resolution of the printer), maintaining the possibility to recognise the printed components compared to the pre-existing elements. However, this procedure depends on the presence of conflicts, which are not always predictable. It may take years before a site gets secured.

5.2 Occurrence of Calamities and Cataclysms

Natural disruptions as earthquakes, landslides, floods, may damage historical buildings, which are not always responsive to these occurrences. If we focus our attention on Italian territory, for instance, in recent times it has been repeatedly hit by seismic events that have caused the irreparable destruction of historical centres, monuments, buildings of architectural relevance (usually made of load-bearing bricks or stones walls) and works of art. Following the earthquake that struck the Emilia Romagna region in 2012, numerous buildings have collapsed and historical architectures were condemned. There are further examples in which the seismic activity has damaged the decorative and structural apparatus of the buildings, though without blocking their use.

The Saint George Cathedral of Ferrara (UNESCO cultural property together with the historic centre of the city itself since 1999), for instance, has suffered numerous degradations, especially of the stone elements of the facade, which are currently under restoration. The collapsed decorative columns are about to be replaced with new elements, made with a numerically controlled subtractive technique (removal of material from an initial marble block) to obtain the resulting shape. The damage to which the cathedral is subjected is fully compatible with additive prototyping interventions.

It can be hypothesized the use of powder bed deposition technology to prototype volumes made of reconstructed stone, whose chemical-physical composition shall be as close as possible to the pre-existing one that composes the facade of the cathedral. The recognisability of new insertions from existing element could be managed by digitally modifying the level of detail of the architectural component to be 3D printed. This methodology could also be applied on buildings made of bricks hybridising the two possible printing technologies, that means extruding the mortar and then superimposing, through powder bed deposition, consecutive layers of *cocciopesto* (that can be obtained by grinding desegregated bricks longer usable) to produce a reconstructed brick.

A possible scenario, to be intended as a schematic visualisation of the process, can be examined in the following image (see Fig. 8), that is a representative example of 3D printing possibilities.

Fig. 8. Simulation of an on-site rapid prototyping intervention of the Novi of Modena's clock tower, in the situation after the first earthquake shock of 2012. It collapsed as a result of a subsequent shock (photo by prof. Pietromaria Davoli and elaboration by Sara Codarin).

5.3 Occurrence of Calamities and Cataclysms

Last example, chosen to be brought in this discussion, is the group of Medieval Monuments in Kosovo. In 2006, the property was inscribed within the *List of World Heritage in Danger* due to several difficulties in its management and conservation stemming from the political instability of the region in which it is located. The reasons given by the UNESCO Committee for this decision are:

- lack of legal status of the property;
- lack of legislative protection of buffer zones;
- lack of implementation of the Management Plan and of active management;

– difficulties to monitor the property due to political instability, post-conflict situation (visits under the Kosovo Stabilisation Force/United Nations Interim Administration Mission in Kosovo escort and lack of guards and security);
– Unsatisfactory state of conservation and maintenance of the property.

The site needs, first of all, short-term measures such as the immediate put in place of appropriate guarding/security arrangements and the preparation of a report on the conditions of the wall paintings and the status of conservation of the works (for example the lead roof of the nave of the Ljevisawa Virgin Church needs an urgent intervention). Then, long-term corrective measures are required, following UNESCO guidelines:

1. ensure the adequate long-term administrative, regulatory protection and management of the property;
2. put in place strong protective regimes for the buffer zones;
3. adequately delineate the boundaries;
4. prepare detailed state of conservation reports as a basis for adapted monitoring, preventative conservation measures, and specific conservation projects to reverse decline;
5. ensure appropriate and timely implementation of the Management Plan.

In this case, the survey procedures are facilitated by the fact that the site is accessible and the monuments are still in an acceptable state. Restoration interventions could include the substitution of deteriorated parts, especially of the envelopes, subjected to the action of time, the weather conditions and the lack of appropriate maintenance. The recovery project would be conservative, with no visible reconstructions that could change the figurative image of the property.

6 Conclusions

The presented case studies have been chosen to enlighten different scenarios in which 3D printing can be applied in substitution or in support of traditional methodologies, intended for the substitution of damaged elements, the integration of building gaps and volumes on the grounds of previously collapsed structures. This, to highlight the historical stratifications present in the architectural system.

Palmyra's archaeological excavations, for instance, due to the fact that original pieces are too deteriorated, does not allow anastylosis interventions. The components needed to reconfigure the destroyed volumes can be 3D printed and then positioned (the additions of the present time have to be declared), in respect of: 1931 *Athens Charter*, 1972 *Italian Charter*, 1964 *Venice Charter*, 1972 *Italian Charter*, 2003 *ICOMOS Charter*.

The restoration of the Cathedral of Ferrara and the Medieval Monuments in Kosovo, which provides more targeted actions, can be performed through additive manufacturing as well, always respecting the principles of the discipline (see Table 1).

Table 1. Analysis of possible innovative restoration interventions on Cultural Heritage

Cultural Heritage example	Current risk typology	Typology of the building	Actual damage of the building	Proposed innovative intervention	Proposed innovative materials
Ancient Site of Palmyra	Ongoing armed conflicts and vandalism actions	Archaeological site of ancient remains of the Roman Empire	Destruction and loss of components and entire volumes	Reproduction of the work to communicate its importance	Possible use of materials that recall the original artifact
Cathedral of Ferrara	Natural disruptions (especially earthquakes)	Historical medieval worship building	Damages on the figurative elements of the facade	3D printing and substitution of the damaged components	Use of a stone-like material similar to the elements of the facade
Medieval Monuments in Kosovo	Lack of maintenance or measures for conservation	Group of historical medieval buildings	Damages due to general deteriorations over time	3D printing and substitution of the damaged components	Use of a stone-like material or reconstructed bricks
Cultural Heritage example	Innovative design process	Innovative construction process	Morphology of the integrations	Figurative language of the intervention	Compliance with Charters requirements
Arch of Palmyra	Processing of the digital model and implementation phase	Use of an automated technology	3D printed monolithic element or plural components	Experimental replica to encourage innovtion	Experimental and cultural dissemination of a work
Cathedral of Ferrara	Processing of the digital model through a 3D printer	Powder bad deposition 3D printing	3D printed monolithic architectural components	Integration of elements with a similar cromia to the originals	1931 Athens Charter, 1972 Italian Charter, 1964 Venice Charter, 1972 Italian Charter, 2003 1COMOS Charter
Medieval Monuments in Kosovo	Processing of the digital model through a 3D printer	Powder bad deposition 3D printing or extrusion	3D printed monolithic or plural architectural components	3D printing and substitution of the damaged components	

If properly applied, 3D printing allows achieving the same formal outcome that would follow a traditional process, but according to a revised methodology.

In other words, we believe that the exposed, classified, applicable technologies guarantee the fulfilment of the requirements of the Charters of Restoration, which theoretically legitimise their use within the contemporary cultural framework.

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