ABSTRACT

The inevitability of the Fourth Industrial Revolution highlights the current lack of innovation within the building process, where the construction site continues to refer to methods strongly rooted in building traditions and narrow technological choices. While the construction industry must manage risks based on economics, labor, and safety, new technologies highlight the need to identify new methodologies to enhance construction roles. Interventions carried out according to a digital data-driven strategy can respond to the growing demand for higher quality with prediclatble times in a complex environment and the need to satisfy the requirements of environmental, social, and economic sustainability. In the current age of automation, it is possible to imagine connecting design and manufacturing in a single workflow with the aim of bringing smart tools from industrial manufacturing such as robots to the building site for the conservation of Cultural Heritage. The protection of the site and existing building elements would entail customizing the on-site operations in a responsive way with respect to the characteristics of boundary conditions and compartmentalization of automated equipment. The creation of a workflow is therefore intended not as a standardization of the design outcomes, but as an updating of the technical phases, combining the technological with the cultural instances. Given the trajectory of digital transformation as an emerging ecosystem, a new conception of the master-builder might represent a balanced point between the advancing technological level in architectural construction methods and the artisanal approach that characterizes interventions on Cultural Heritage. The new master-builder constitutes a synthetic figure between the various actors operating in the complex building process. The new master-builder can also be the promoter of the project culture and the supervisor of all the design - construction - management activities that take place in the digital continuum. Decades of positive industry outcomes and recent research advancements in CAD/CAM, with focus on additive manufacturing, allow for the evaluation of successful experiments on the production of customized technological units and informed digital architectures.

Keywords: Robotics, Additive Layer Manufacturing, Cultural Heritage, Conservation, Fourth Industrial Revolution, Digital Workflows.

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Innovative construction systems within building processes.
An approach to large-scale robotic Additive Layer Manufacturing
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University of Ferrara | Department of Architecture

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Dear Eva,

It will be almost a month since you wrote to me and you have possibly forgotten your state of mind (I doubt it though). You seem the same as always, and being you, hate every minute of it. Don't! Learn to say "Fuck You" to the world once in a while. You have every right to. Just stop thinking, worrying, looking over your shoulder, wondering, doubting, fearing, hurting, hoping for some easy way out, struggling, grasping, confusing, itching, scratching, mumbling, bumbling, grumbling, humbling, stumbling, numbling, rambling, gambling, tumbling, scumbling, scrambling, hitching, hatching, bitching, moaning, groaning, honing, boning, horse-shitting, hair-splitting, nit-picking, piss-trickling, nose sticking, ass-gouging, eyeball-poking, finger-pointing, alleyway-sneaking, long waiting, small stepping, evil-eyeing, back-scratching, searching, perching, besmirching, grinding, grinding, grinding away at yourself. Stop it and just:

DO

I have much confidence in you and even though you are tormenting yourself, the work you do is very good. Try to do some BAD work — the worst you can think of and see what happens but mainly relax and let everything go to hell — you are not responsible for the world — you are only responsible for your work — so DO IT. And don't think that your work has to conform to any preconceived form, idea or flavor. It can be anything you want it to be. But if life would be easier for you if you stopped working — then stop. Don't punish yourself. However, I think that it is so deeply engrained in you that it would be easier to:

DO

Much love to you.

Sol

Sol Le Witt's letter to Eva Hesse, 1965.[1]
[Letters of Note: Correspondence Deserving of a Wider Audience]

1 The letter read and interprereted by Benedict Cumberbatch: https://vimeo.com/386532933.

To the philosophy,
rightly defined naught but the love of wisdom.
[Cicero]

PART I - INTRODUCTION

1 Presentation of the research

ABSTRACT

The inevitability of the Fourth Industrial Revolution highlights the current lack of innovation within the building process, where the construction site continues to refer to methods strongly rooted in building traditions and narrow technological choices. While the construction industry must manage risks based on economics, labor, and safety, new technologies highlight the need to identify new methodologies to enhance construction roles. Interventions carried out according to a digital data-driven strategy can respond to the growing demand for higher quality with prediclatble times in a complex environment and the need to satisfy the requirements of environmental, social, and economic sustainability.

In the current age of automation, it is possible to imagine connecting design and manufacturing in a single workflow with the aim of bringing smart tools from industrial manufacturing such as robots to the building site for the conservation of Cultural Heritage. The protection of the site and existing building elements would entail customizing the on-site operations in a responsive way with respect to the characteristics of boundary conditions and compartmentalization of automated equipment. The creation of a workflow is therefore intended not as a standardization of the design outcomes, but as an updating of the technical phases, combining the technological with the cultural instances.

Given the trajectory of digital transformation as an emerging ecosystem, a new conception of the master-builder might represent a balanced point between the advancing technological level in architectural construction methods and the artisanal approach that characterizes interventions on Cultural Heritage. The new master-builder constitutes a synthetic figure between the various actors operating in the complex building process. The new master-builder can also be the promoter of the project culture and the supervisor of all the design - construction - management activities that take place in the digital continuum. Decades of positive industry outcomes and recent research advancements in CAD/CAM, with focus on additive manufacturing, allow for the evaluation of successful experiments on the production of customized technological units and informed digital architectures.

Keywords: *Robotics*, *Additive Layer Manufacturing*, *Cultural Heritage, Conservation, Fourth Industrial Revolution, Digital Workflows.*

1.1 Background of the scientific problem

"The machines are leaving the cage" [German Federal Ministry of Labor and Social Affairs, 2016]

The doctoral thesis investigates the opportunities offered by the changes taking place on a global scale concerning the process and product innovation within the framework of the Fourth Industrial Revolution[1] in order to redefine the design and operational workflows within the recovery and preservation of Cultural Heritage buildings. In this context the term Fourth Industrial Revolution is considered to be synonymous with other terms including: Industry 4.0 or Second Machine Age or Industrial Renaissance. This socio-technical ecosystem entails methodological and operational changes that have repercussions in the decision-making phases of the architectural project, which opens up to an era of new and unexplored possibilities for environmental and technological design at all scales, from the construction unit to the technological system. These procedural possibilities are investigated with respect to different lines of research that unite and integrate in a single workflow computation and digital manufacturing processes.

1.1.1 Technological shift and need for a multidisciplinary approach

Today the technological sectors are mixing together, connecting various disciplines and skills. In architecture, operating technological transfers from multiple multidisciplinary sectors are also connecting multiple skills. An acknowledgment is inevitable that it is no longer sufficient to consider architectural design as a separate field in this broader system. In the present era, defined by the term Anthropocene (Crutzen, 2006), different technologies are increasingly evolving towards the definition of an interconnected ecosystem, which characterizes the global artificial layer called technosphere (Zalasiewicz et al., 2017). The systemic evolution in the productive culture is framed in terms of the Fourth Industrial Revolution (Schwab, 2017), changes that include advances in big data, augmented reality, artificial intelligence, machine learning, social networks, analytics, and cloud storage in the post-work and post-digital society. Compared to previous revolutions, it occurred more quickly and is characterized by ubiquity and intercommunication of the means of production. Restricting

1 About the Fourth Industrial Revolution multiple definitions have spread: "Especially in Germany, a vivid public debate about "industry 4.0" has developed in recent years. It advances the argument that industry 4.0 is the Fourth Industrial Revolution that follows on from technological revolutions brought about by water and steam power (industrial revolution 1.0), electric power (industrial revolution 2.0), and computing/computerised automation (industrial revolution 3.0)". See: https://www.triple-c.at/index.php/tripleC/article/view/1010.

this discussion to the architecture sector, the results of the Fourth Industrial Revolution have been theorized as the Second Digital Turn (Carpo, 2017), which has been configured as the introduction of automated tools for customized production within the design process. Second Digital Turn assumes that a previous phase change occurred. This previous change happened in the1990s, when the architectural design sector began to absorb digital workflows from the naval and aeronautic industries. The so-called First Digital Revolution or Digital Turn (Carpo, 2013), introduced a new design culture contributing to the spread of computational thinking and digital tectonics, enabling architects to interface with common language, reduce uncertainties, and ensure greater awareness in decision-making phases.

The First Digital Revolution was represented by formal elaboration of the digital environment and two-dimensional simulations, resulting in a secondary role for material culture. The decade that followed 2010 witnessed a push towards innovation of obsolete organizational structures related to design production of architecture and human labor related to construction. The Second Digital Turn is characterized by tools that are programmable to materialize the digital space with greater flexibility, without the limitations imposed by standardized production methods. The new tools allow for the investigation of what Neil Gershenfeld defined in 2012 as the Digital Fabrication Revolution, which expresses itself with the possibility of "turning data into things" (Gershenfeld, 2012). This revolution is defined through a *digital continuum* that compresses the space between design and production, elevating the impact of material culture. Consequently, design output links between the conceptual phase and the built result, as in the past with craft traditions. with the Digital Fabrication Revolution, design is not separated from construction and the translation between one and the other becomes nearly instantaneous. The resulting *digital continuum* defines an opportunity to bring back the master-builder, as an expression of digital complexity and dexterity. Moreover, it can lead to pioneering conceptual results and renewed aesthetic paradigms (Figliola, 2019) pointing towards the possibility of transforming roles and disciplines of professionals working together within the digital environment. Digital manufacturing technologies (robotic arms, 3D printers, smart-assembly or combined tools, to name a few) occupy a fundamental role in this scenario. These technologies are the foundations for mass-customization and performative architecture. This ongoing cultural breakthrough with the Second Digital Turn aims to make the digital space tangible and perceivable (Gramazio and Kohler 2008), filling the gap left by the First Digital Turn (Figliola, 2019), which failed to develop aesthetic and material sense (Picon, 2014) in architectural production.

1.1.2 Digital Heritage and demand of customized production

Several demonstrations of damage, destruction, and loss of the collective Architectural Heritage are being witnessed recently. At the European level, these issues are emerging in an increasingly incisive way. The scientific community systematized the knowledge on this theme through community research programs aimed, where possible, at preserving the historic Architectural Heritage. The *UNESCO List of World Heritage in Danger* is a reference document that contributes to the definition of risk and damage conditions to the existing Heritage. The document contains information relating to the geographical and socio-economic context for which each heritage site records the examination, maintenance status, and priority actions to be taken for protection. The main risks are collected and analyzed, including neglect, abandonment, ongoing conflicts, environmental issues, natural disruptions, and vandalism. Currently, also as a result of the *Declaration of Cooperation on Advancing Digitization of Cultural Heritage 2019* document, Heritage conservation is adapting to the contemporary needs of digitalization of buildings in their *de facto* state. The digitization is understood as a decisive moment in the decision-making process of future intervention choices. The European Heritage is expected to be fully digitized by 2025. The use of digital tools in this sector today is limited to surveying and diagnostics, with the aim of facilitating management, conservation, and programmatic operations. However, the recovery site of the existing structure has an optimization margin deriving from the current availability of production tools capable of reducing the complexity of the production chain of customized architectural elements. The recovery site of the existing, more than others, requires the resolution of problems on a *case-by-case* basis, often with decisions taken directly on-site, given the geometric uniqueness of the buildings. *Case-by-case* design solutions are the result of unpredictable variables such as the lack of information about building geometry, assembly materials, and possible structural instabilities.

The context of the Fourth Industrial Revolution highlights the current lack of innovation within the building process, where the construction site continues to refer to methods strongly rooted in building traditions and narrow technological choices. While the construction industry must manage risks based on economics, labor, and safety, new technologies highlight the need to identify new methodologies to enhance construction roles. The interventions carried out according to a digital data-driven strategy can respond to the growing demand for higher quality with reduced times in a complex environment and the need to satisfy the requirements of environmental, social, and economic sustainability. In the current age of automation, it is possible to imagine connecting design and manufacturing in a single workflow with the aim of bringing smart industrial robots to the recovery site. The protection of the site and existing building elements would entail customizing the on-site operations in a responsive way with respect to the characteristics of boundary conditions and compartmentalization of automated tools. The creation of a workflow is therefore intended not as a standardization of the design outcomes, but as an updating of the technical phases, combining the technological with the cultural instances.

Given the inevitable digital transformation, a new conception of the master-builder might represent a balanced point between the current technological level in architectural construction methods and the artisanal approach that characterizes interventions on Cultural Heritage. The new master-builder constitutes a synthetic figure between the various actors operating in the complex building process. The new master-builder can also be the promoter of the project culture and the supervisor of all the design - construction - management activities that take place in the *digital continuum*. Decades of positive industry outcomes and recent research advancements in CAD / CAM (computer aided design / computer aided manufacturing) allow for the evaluation of successful experiments on the production of informed digital architectures. Off-site automation is currently very common. As a result, a simplified and flexible organization on the site, a cross-check of planned phases, a repeatability of different circumstances, and a reliability of outcome over time are expected. It is relevant to explore the advancement of scientific knowledge within the restoration field. Digital technologies and fabrication tools such as additive manufacturing could support the decision-making phases for innovative interventions on Cultural Heritage and be exploited to support design outcomes.

1.2 Limitation of the scope of the investigation

This doctoral thesis investigates the relationship between the Fourth Industrial Revolution and the consequences on Cultural Heritage. The research was framed to explore digital workflows and applications in order to validate feasibility and technical hypotheses as well as an aid in the definition of objectives and expected results. The limitation of investigation was developed in two research areas, recovery of Cultural Heritage and robotic construction, through the definition of some key concepts of the dissertation itself. The dissertation text refers to recurring concepts that are described below according to the specific use of this study.

1.2.1 Cultural Heritage

Historical sources report that since the time of the ancient Romans, there was an awareness of the cultural value of human-made works. In the VI century BC, the king Theodoric the Great referred to the seven Wonders of the World in one of his writings, encouraging the Romans to produce monuments that would become more renowned than those of the past. In these words, it is inherent the concept of transmission to the future of the scientific and technological acquisitions of the time. Identity is embedded in material and civilizations. With reference to architecture, over the centuries (through the Middle Ages, Renaissance, Baroque and Neoclassical) monuments have been the object of study by scholars from all over the world. However, a united definition of Heritage has never emerged. The restoration charters of the twentieth century have helped to give concreteness to the concept of valuable material objects to be preserved.

This thesis takes as reference the definition of Cultural Heritage expressed by UNESCO in the *Convention Concerning the Protection of the World Cultural and Natural Heritage* of 1972.[2] The document drafted following the first conference brings together the concepts of "common interest", "outstanding importance" and "universal value" to spread the sense that heritage is collective and concerns the whole of humanity without temporal or geographical distinctions. The first article describes the definition of Cultural Heritage establishing that they can be considered as such:

- monuments: architectural works, works of monumental sculpture and painting, elements or structures of an archaeological nature, inscriptions, cave dwellings and combinations of features, which are of outstanding universal value from the point of view of history, art or science;
- groups of buildings: groups of separate or connected buildings which, because of their architecture, their homogeneity or their place in the landscape, are of outstanding universal value from the point of view of history, art or science;
- sites: works of man or the combined works of nature and man, and areas including archaeological sites which are of outstanding universal value from the historical, aesthetic, ethnological or anthropological point of view.

2 Convention Concerning the Protection of the World Cultural and Natural Heritage, UNESCO: https://whc.unesco.org/en/conventiontext/.

In addition, as later specified in the *Medium Term Plan 1990-1995*,[3] "as a constituent part of the affirmation and enrichment of cultural identities, as a legacy belonging to all humankind, the cultural heritage gives each particular place its recognizable features and is the storehouse of human experience". As a consequence, "the preservation and the presentation of the Cultural Heritage are therefore a corner-stone of any cultural policy". Finally, "the Cultural Heritage should be considered both in time and in space. First, it no longer stops at the dawn of the nineteenth century but now also embraces the records left behind by the twentieth century" (Jokilehto, 2005). This research is interested in the architectural subset, of the comprehensive Cultural Heritage definition. The tangible[4] Cultural Heritage were explored. The buildings in conditions of risk due to degradation were taken into account.

1.2.2 Conservation of Cultural Heritage

The conservation of Cultural Heritage may be defined as the combination of "all measures and actions aimed at safeguarding tangible Cultural Heritage while ensuring its accessibility to present and future generations. Conservation embraces preventive conservation, remedial conservation, and restoration. All measures and actions should respect the significance and the physical properties of the Cultural Heritage item".[5] In other words, conservation "refers to the discipline involving treatment, preventive care, and research directed toward the long-term safekeeping of cultural and natural Heritage".[6] The dissertation aims to treat the theme of conservation as an opportunity for study and as an acknowledgement of the responsibilities of architects to approach the topic with diligence and critical mindset. Therefore, the term may be enriched by referring to the Nara Conference on Authenticity within the World Heritage Convention of 1994. In this instance, the general concept of conservation was elaborated as "all efforts designed to understand Cultural Heritage, know its history and meaning, ensure its material safeguard and, as required, its presentation, restoration and enhancement".[7] This research does not want to establish a theoretical outline for the use of robotics in Cultural Heritage. The intent is to introduce and -systematize the tools that can be used by architects in the framework of the Fourth Industrial Revolution. Through these tools, professionals will be able

3 UNESCO. General Conference, 25th session, 1989: https://unesdoc.unesco.org/ark:/48223/pf0000084697. Criteria for selection of the World Cultural Heritage: https://whc.unesco.org/en/criteria/.
4 Tangible Heritage: http://www.unesco.org/new/en/culture/themes/illicit-trafficking-of-cultural-property/unesco-database-of-national-cultural-heritage-laws/frequently-asked-questions/definition-of-the-cultural-heritage/.
5 ICOM-CC: http://www.icom-cc.org/242/about/terminology-for-conservation/.
6 AATOnline ID 300054238.
7 Nara Conference on Authenticity in Relation to the World Heritage Convention, held at Nara, Japan, from 1-6 November 1994. Available at: http://ip51.icomos.org/~fleblanc/documents/terminology/doc_terminology_e.html.

to best express their skills in managing complex construction conditions optimizing the quality of the result. The conservation expert must be aware of the materials, the history of the buildings, and the design culture in order to best convey the idea of Cultural Heritage conservation.

1.2.3 Robotics

The definition of a robot has significantly changed since the first sketch of a robot knight made by Leonardo Da Vinci in 1497. The idea of automatic mechanical machines has developed over centuries, especially in the visionary projects of physicists and mathematicians. The knowledge on the topic led to the elaboration of the multi-axis-anthropomorphic robots, which are based on the patent *Programmed Article Transfer*, filed by George Devol in 1954.[8] At an international level, the Robotics Industries Association (RIA)[9] defines a robot as: "a reprogrammable, multifunctional manipulator designed to move material, parts, tools or specialized devices through variable programmed motions for the performance of a variety of tasks". Since the second half of the last century, several generations of robots have followed. Starting from the first generation, when robots were only able to carry out a predefined sequence of actions, the applied research has moved on to the development of intelligent, communicative, and collaborative robots. They can adapt flexibly to changing external conditions or inputs. Among the many sectors in which robots are applied, from manufacturing to services, the industrial robots are the object of investigation.

In the topic, the International Federation of Robotics (IFR)[10] adopts the definition given by the International Organization for Standardization: ISO 8373:2012 "Robots and robotic devices".[11] An industrial robot is an "automatically controlled, reprogrammable,[12] multipurpose[13] manipulator, programmable in three or more axes, which can be either fixed in place or mobile for use in industrial automation applications. The industrial robot includes the manipulator, the actuators, the controller, the teach pendant, and any communication interface (hardware and software)". In particular, the manipulator is intended as a "machine in which the mechanism usually consists of a series of segments, jointed or sliding relative to one another, for the purpose of grasping and/or moving objects (pieces or tools) usually in several degrees of freedom."[14] A retired industrial robot from the automotive industry was used to carry out an experiment in the course of this research. The purpose was to perform tasks in a customized digital-making perspective, differently form the logics of mass production that are based on seriality and standardization. The laboratory that provided the thesis

8 George Devol's patent "Programmed article transfer" no. 2.988.237: https://www.invent.org/inductees/george-devol. It is the first reprogrammable robotic arm. In 1946 he patented a device for controlling machines.

9 Robotics Industries Association, funded in Ann Arbor (MI) in 1974: https://www.robotics.org/.

10 IFR: https://ifr.org/industrial-robots.

11 ISO 8373:2012: https://www.iso.org/obp/ui/#iso:std:iso:8373:ed-2:v1:en:term:3.11.

12 ISO 8373:2012. Def. 2.4. Reprogrammable means that a robot is "designed so that the programmed motions or auxiliary functions can be changed without physical alteration".

13 ISO 8373:2012. Def. 2.5. Multipurpose implies that a robot is "capable of being adapted to a different application with physical alteration".

14ISO 8373:2012 "Robots and robotic devices".

with the necessary tools to carry out the work had a robot without sensors or feedback systems. The value of the experiment was to determine the limits and potentials of a fabrication-aware workflow that is made accessible through basic knowledge acquired at the level of university education.

1.2.4 Large-scale Additive Layer Manufacturing

Additive manufacturing began in the 1980's, when Hideo Kodama of Nagoya Municipal Industrial Research Institute patented an application for rapid prototyping. The aim of this technology was to fabricate three-dimensional scale models with UV exposure to polymers. Since then, several technology developments followed. Extracting the concept from the technical aspects, from the geometries of the machines used to produce the prototypes and from the materials that can be used, the definition provided by the Gartner Glossary can be used.[15] It states that: additive manufacturing is the capability to create a physical object from a digitally encoded design through the deposition of material via a 3D printing process. In this regard, 3D printing is now widely used to refer to additive production methods. In truth, this is the name under which engineers Alain Le Méhauté, Olivier de Witte, and Jean Claude André filed a patent for a stereolithography process. Stereolithography is a subset of additive production, which occurs exclusively through a photochemical process for the solidification of liquid polymers.

In 2009, the ASTM, American Society for Testing and Materials[16] published the first Standard terminology for Additive Manufacturing Technologies (F2792), calling it revolutionary. The description includes information about the upstream workflow and the matter used for the translation from digital to physical: "Additive manufacturing (AM) is the revolutionary process of creating three-dimensional objects by the successive addition of material – whether plastic, metal, ceramic, composite, or something else. The process starts with a digital model, usually generated by computer-aided design. Selecting from a variety of specialty AM equipment, users can take just about any shape they design digitally and create it in the real world. This is fundamentally different from traditional manufacturing methods, which either use molds and dyes to shape the raw material, or cut and grind away unwanted excess material from a solid starting block to create the desired result".[17]

This research is interested in scaling up the additive manufacturing process, to understand the opportunities for architecture. Until now, the large-scale AM, or more precisely ALM, has been tested mainly through custom prefabrication, which explored new creative possibilities at the expense of time and cost optimization. The practical objective of this work is to try to address additive manufacturing towards additive construction, which "represents the entire process of building a digital form from materials produced on-site that are then deposited according to a digital model" (Labonnote et al.,

15 Gartner IT Glossary, Additive Manufacturing: https://www.gartner.com/en/information-technology/glossary/additive-manufacturing.

16 American Society for Testing and Materials: https://www.astm.org/.

17 The 5 Most Important Standards in Additive Manufacturing in ASTM. Available at: https://www.astm.org/standardization-news/?q=features/5-most-important-standards-additive-manufacturing-.html.

2016). As the goal is to bring together Cultural Heritage conservation and additive manufacturing, there are many aspects to take into account, both in technical and theoretical terms.

1.2.5 Digitalization of building processes

In this research, the digitization of the design process means the development of the phases from the identification of the concept to the definition of the executive documents in a digitally-driven way. The phases "are characterized by dynamic, open-ended and unpredictable but consistent transformation of three-dimensional structures that give rise to new architectonic possibilities" (Kolarevic, 2004). The fluidity that characterizes the process has been defined as the digital continuum (Leach, 2002). It refers to the use of the digital model as a means of interface and communication between the professionals involved in the implementation of the work.

Process innovation came into architecture with the digital revolution of the 1990s's, resulting from the diffusion of software leveraging cheap processing power and the introduction of graphic interfaces. This period marked the transition from mechanical to digital technologies. Before the spread in design for the construction industry, several sectors had been pioneering for decades the potential of digitization. The digital design workflows arrived from the industrial fields for the production of boats, planes, and cars. These products are entirely designed, developed, analyzed and tested in a digital environment. As with aerospace engineers, shipbuilders no longer use drawings for the construction of these high-tech products with the utmost precision, but perform design processes with a comprehensive three-dimensional digital model from design to production. The productive part is particularly relevant in the context of the current Fourth Industrial Revolution (following the phases of hand-making, mechanical-making, and digital-making), because now rather than in the past, the implications of digitization have repercussions on the translation between computer-aided design and computer-aided manufacturing. The spread of digital workflows in professional practice has meant that architects could use computational data to inform building production. Design time previously spent on drawings has been transformed because digital models more closely represent reality, eliminating the necessity of 2D, static drawings. In other words, the digital workflows, the ubiquity of the machines and the ongoing shift in the project culture allows to overcome the concept of “division of responsibility that make the production of drawings necessary” (Kolarevic, 2004).

The overcoming of static models is today also demonstrated by the direction in which the academic system is headed, as it is entrusted with the training of the next generation of architects. In universities, the use of Gravity Sketch is spreading. It is a design software that works in virtual reality. By using Oculus Rift and controllers, it allows the creation of shapes in three dimensions through body gestures. This approach leads one to think about the relationship between surfaces, volumes, and the human body. The abstraction of 2D drawings is not needed to understand the design outcome. This could be the key to revolutionising the design process[18] and maximising the potential of digitization.

18 Five Industries Virtual Reality Is Changing, in *Forbes*: https://www.forbes.com/sites/leifwalcutt/2016/10/13/not-just-gaming-5-industries-virtual-reality-is-changing/.

1.2.6 Industrialization of building products

In the construction industry, industrialization means the delocalization of the realization of standardized technological elements for their repetitive production. The advent of industrialization in the building sector weakened the connection between design and construction. Industrialization "has determined a flattening of the artisan interpretation" and has brought constraints to the design determined by the downstream production technologies (Spadolini, 1981). This has inevitably led to restrictions in the work of the architect, forced to limit formal and constructive choices based on industrial production. It also distilled the professional role of the contemporary architect, who now must assume the availability of off-the-shelf components (Groak, 2002).

In the 1980's, in a period of strong technical experimentation in Europe, Pierluigi Spadolini systematized building construction dividing the production of the technological units into three categories:

- industrial, for which the products are made with the same invariable characteristics;
- semi-industrial, whereby products can be made with different characteristics within the limits of technology and assembly methods;
- craft, so the products are made on-site based on the manual labor capacity and within the material limits. The artisanal construction means that the designer is a central figure for the development of all phases.

In the 1050’s and 1960’s closed prefabrication was a widespread construction practice. It is characterized by the rigidity of mass production, for which it is possible to reproduce constructive components in a serial and cost-effective manner while eliminating the inaccuracies of craftsmanship. It is based on a limited use of materials, the use of efficient but at the same time standardizing productive systems, limited / de-skilled labor, and, to many, the perception of detrimental architectural quality. In the 1980’s, a period of strong technical experimentation, architects worked with open, more flexible, and resilient prefabrication systems. This approach allowed for variations in production, enabling designers to work with greater design freedom on materials and components. The designer assumed the availability of special variations. This approach constituted the productive context within which the first theorization on mass-customization was hypothesized. In this way, the idea of a production process was introduced through which to produce differentiated elements with the same economic efficiency with which the standardized ones are produced (Davis, 1997).

The Fourth Industrial Revolution and the spread of robotization, opens to scenarios of customized on-site and off-site production, offering the possibility to explore formal possibilities without constraints dictated by traditional production systems. This approach will bring design and production closer together in a single digital workflow. In the next future, contractors will be able to produce technological units to be aggregated on the project site, minimizing the consumption of resources in the production chain and the expenses related to the transport of construction components. These possibilities encourage experimentation on innovative, non-invasive, and reversible aggregation systems, in favor of open prefabrication and mass customization, able to provide differentiated answers compared to complex design input.

1.3 Motivations to undertake the research

This chapter section identifies broader areas of knowledge in which this research is located. The objectives of the research are framed through objectives tied to this broader knowledge base. Care has been taken to highlight unresolved elements in the culture of existing contemporary design that must be addressed in the short term to bring the speculation of this research to fruition. The unresolved elements in the culture of existing contemporary design can only be resolved by virtue of substantial economic, technological, and social changes.

The notion of the Fourth Industrial Revolution began at the end of the 1990s and characterized the evolution of increasingly integrated and sophisticated technologies. The Fourth Industrial Revolution established itself on the basis of a digital revolution infrastructure. The main consequence of this revolution was the acknowledgment that "the world is at an inflection point where the effect of these digital technologies will manifest with full force through automation and unprecedented making" (Brynjolfsson and McAfee, 2014). The revolution is characterized by much more ubiquitous and mobile internet, and through the emergence of AI and machine learning (Schwab, 2017).

With the Fourth Industrial Revolution more technologies are getting used and connected online faster and sooner. Massive changes are happening faster than any other previous revolution through increased connectivity, instant communication, and established infrastructure systems. As a result, new ideas and products can spread at speeds never seen before. Unfortunately these widespread changes are not yet hitting the construction industry. Designers must understand and integrate these changes in order to pioneer opportunities for new workflows and new systems for architecture.

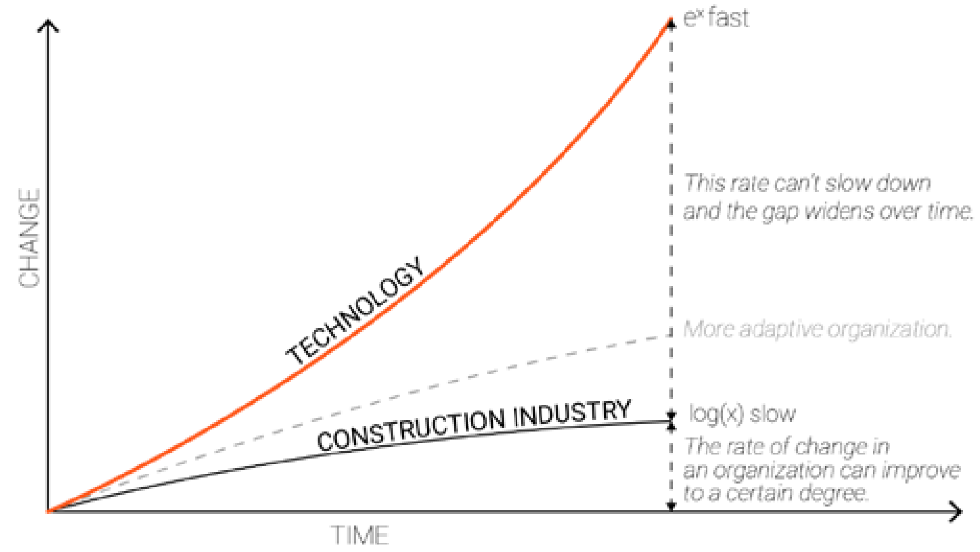
Designers must be able to direct change and:

- expand their skills to be able to work by exploiting the potential of computational design, digital fabrication, scripting and materials engineering to start interactions across the digital and physical world;
- incorporate AI, machine learning, automation technologies, ALM, and robotics in a flexible way, within their design workflows.

However, rapid technological development is not always accompanied by the same rate of acceptance on the part of society and organizations to absorb change. This acceleration of technological change is known as Moore's Law. To view this change / time equation, you can refer to Martec's Law[19] (Fig. 1.1), according to which technology changes exponentially, while organizations change at a logarithmic rate, much slower.[20] There is an increasing divide between the devices that we use and the culture of their use. In order for this area to become more adaptive and flexible, for the purpose of customization and the creation of new models, the actors involved in the process must:

19 The Marketing Technology Conference: https://martechconf.com/.

20 Martec's Law: https://chiefmartec.com/2016/11/martecs-law-great-management-challenge-21st- century/.



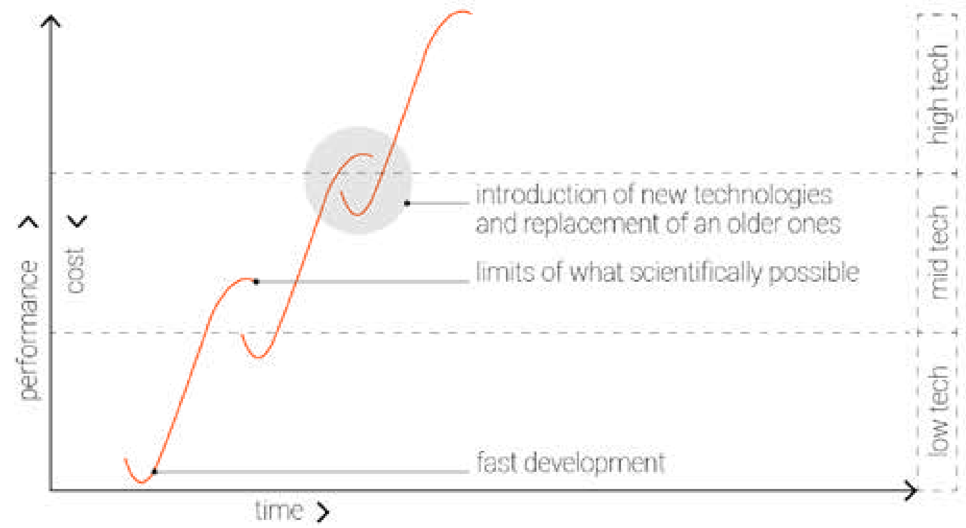


Fig. 1.1 Martec's Law. Technology changes exponentially (fast), yet organizations change logarithmically (slow). It expresses the management challenges of our time. Source: https://www.visualcapitalist.com/rising-speed-technological-adoption/.

Fig. 1.2 The "S" curve of innovation or Foster's Curve (1986). Source: Foster, R.N., 1988. Innovation: The attacker's advantage. Summit books. P. 28.

- decide which technology changes to embrace and which to forgo;
- choose the few technologies that have the greatest potential impact in the future.

The exponential trend of technological development can also be analyzed from the point of view of scientific progress and the replacement of old systems with new systems. Through Foster's curve (Fig. 1.2), or "S" curve of technology, it is possible to deduce the time / performance ratio of a given technology and its transition from low to high tech. Following the first market release, the technology improves performance exponentially with a reduction in cost. Once the scientifically possible development limit is reached, new technology is introduced.

The construction industry is particularly reluctant to accept change and consequently the restoration of monument architecture must take even greater care to manage risk (Fig. 1.3). The main operational obstacle is the cultural mindset which must be overcome before technological development imposes the inevitability for necessary advancements of first world economies. Despite this, the research sector is pushing towards the attainment of the scientific limit of development of technologies that could revolutionize the way of building. Anthropomorphic industrial robots were the machines on which there was a greater developmental push. By 1970s robots in manufacturing facilities responded only to simple input commands. Commands and feedback technologies were still basic. Now robots are smart. They are equipped with sensors reacting to environmental stimuli which, integrated with AI, provide the machine with decision-making capabilities. Following this development cycle and new advances, robots will truly represent an extension of our motor and cognitive abilities. When these techniques succeed, the construction industry will be able to manage new ways of building that do not follow traditional logics.

The adoption of technologies and the digital infrastructures that support them are characteristics of the first world economies, where the Fourth Industrial Revolution is instigating profound change in the structure of organizations. Industrial culture is shifting towards Work 4.0, which envisages human-machine collaboration as a cornerstone. The document *Re-Imagining Work: White Paper Work 4.0*, written by the Federal Ministry of Labor and Social Affairs of Germany (Work, 2016) states: "in industrial manufacturing, a new generation of robots is emerging with progressive advances in AI. While in recent decades robots were primarily used to automate simple production steps, the latest industrial robots are now also capable, thanks to AI-based high-performance sensors, to take on fine-motor tasks and to interact with their human co-workers. These "cobots" (short for "collaborative robots") perceive their surroundings in different ways, paving the way for safe physical human-machine collaboration" (Work, 2016).

The previous spatial separation of people and robots is becoming irrelevant; the machines are leaving the cage, "adventuring into our world",[21] questioning the role of human experience and making skilled-work obsolete. As the existing workforce ages and retires, the industry must figure out what

21 Formant platform: https://formant.io/news-and-blog/2019/10/01/company-updates/formant-launches-platform-to-observe-analyze-and-operate-robot-fleets/. Formant is a platform that manages cloud-based robot fleet.

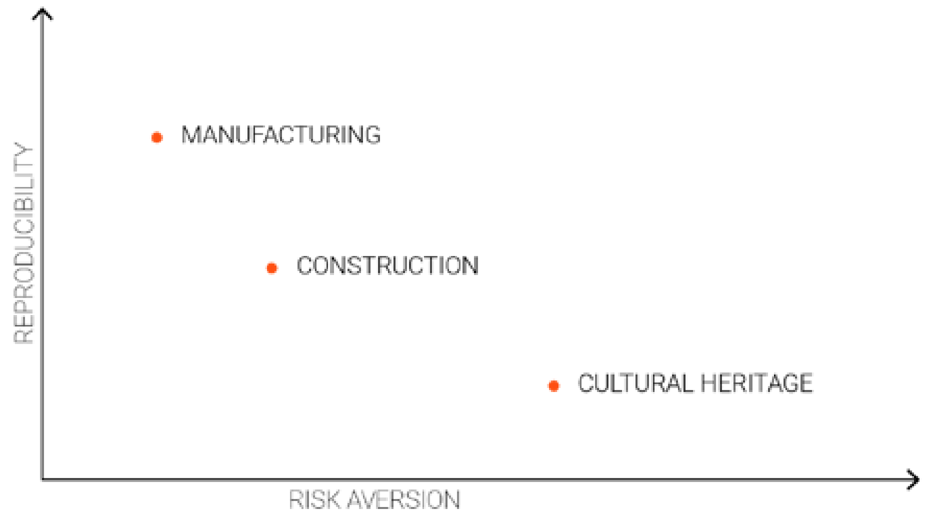


Fig. 1.3 Relation reproducibility/risk aversion in production.
Fig. 1.4 QxS=CxT linear function vs QxS>CxT parabolic function in production. Source: Kieran, S. and Timberlake, J., 2004. *Refabricating architecture: How manufacturing methodologies are poised to transform building construction.* McGraw Hill Professional. P.10.

to do as young workers are selecting different career paths. In this scenario, the first world economy undergoes a transition to a knowledge economy, where the figure of the master-builder becomes the protagonist as a professional who has intellectual control of the processes and instructs the tools on how to operate.

In terms of performance trends, consumer and client expectations increase for higher quality of construction in less time and lower costs (Fig. 1.4). The linear relation Q (quality) x S (scope) = C (cost) x T (time) relative to the realization of a typical product of manufacturing has become exponential Q x S > C x T through the introduction in the processes of standardized prefabrication of components[22] (Kieran and Timberlake, 2004). Rethinking these commonly held beliefs might also benefit designers where exponential profit / revenue ratio might be possible through automation of processes and introduction of new technologies. The arguments set out above can be summarized in the following table. The designer / master-builder is able to systemize knowledge in terms of production, labor, technology, and culture.

Fourth Industrial Revolution	Craftsmanship	Customization	Work 4.0
- interconnected tools - direct relation between virtual and physical world - need for new skills: computing, scripting	- workforce will retire - skilled workers are expensive - current organization of work will be obsolete by one decade	- demand for better quality and scope - demand for customized products - demand for data driven performance	- human-machine collaborations - machine is trained to perform tasks - experience is replaced by AI
DESIGN PROBLEM FOR THE MASTER-BUILDER who understands labor, technology, and culture			
DESIGN AND CULTURAL HERITAGE very unique design problem			

22 Q(uality) x S(cope) = C(ost) x T(ime). "Quality and scope are desirable aspects of anything we make. We like things that are well made. When they are well made, we say they are crafted. Cost and time, however are not desirable elements. They are the limits that determine how much quality land scope we can attain. While we might want more, quality and scope, we still want to spend less time and money. In classical process-engineering terms, the way to attain a certain combination of higher quality and greater scope is to spend some combination of more time and more money". Q(uality) x S(cope) = C(ost) x T(ime). "Cars, ships, and planes must even move through space, while buildings, relatively static artifacts, are rooted in place. Ships are larger than most buildings and generally dynamic. It is too easy to dismiss these examples as having no relevance for architecture, which is fixed to the ground and custom crafted in the field rather than factory produced. There are lessons that can be transferred from our sister industries to architecture. These lessons are about processes and materials developed over the past decade that have overturned the ancient equilibrium between expenditure of resources and acquisition of benefits." Kieran, S. and Timberlake, J., 2004. Refabricating architecture: How manufacturing methodologies are poised to transform building construction. McGraw Hill Professional, pp.8-11.

1.4 Objectives

Through the introduction and scientific framing of research it emerged that these two areas that are evolving independently:

1) robotic automation in the construction sector
2) digitization for Cultural Heritage conservation

The potential offered by the relationship between the two areas has the main objective of the thesis to integrate robotics and Cultural Heritage as an opportunity to bring the master-builder back into professional architecture practice. The approach leads to wider implications for designers in terms of agency and impact.

Given these premises:

- need for customization of the construction components for the restoration project and a technical shift that will change the performance of smart machines;
- high qualitative demand to be able to satisfy through data driven project strategies;
- potential of computational models and scripting to optimize design processes;
- potential for smart automation and digital fabrication to optimize production processes.

This research seeks to define:

1. **a hypothetical experimental workflow**, or methodological strategy, to hypothesize the use of on-site automation on the sites of Cultural Heritage recovery. This work serves to introduce the topic in the research sector and to deepen the cultural approach to the topic. Workflow must combine survey and diagnostics of an architectural cultural asset advancing both speed and accuracy through the use of computational design / scripting and customized production through digital fabrication. The specific objective of the workflow is given by the definition of a design approach that combines the cultural demands with the development of implementation techniques.

2. **a laboratory experiment to support the case**. According to the limitation of the scope of the investigation, the experiment will create a robotic end-effector using robotic additive manufacturing simulating the interaction with a pre-existence and the respective geometric constraints as a means of prototyping the proposed workflow. After acknowledging the state of knowledge in this sector, contribute to the advancement of the TRL (technology readiness level) in academic research.

By achieving these objectives, it will be possible to determine the potential and criticality of this process in order to direct future academic research in view of a possible strategic integration into the building construction process.

1.5 Methodology and tools

The research was developed following an inductive method, moving from a succession of unique cases to broad explanatory principles (Cross,1984). It was based on the observation of qualitative phenomena[23] (Creswell and Creswell, 2017) which laid the foundations for an analytic journey "that leads further into data and suggests additional relationships" (Yin, 2017). The construction of knowledge has been addressed to the systematization of an applied operational strategy, so that "the solution to a research problem has practical consequences" (Booth et al., 2003).

The three doctoral years are configured as: three initial semesters of study and individual work, an academic year of applied research and a final semester of systematization of the information collected and drafting of the thesis. The work carried out can be divided into four phases (called WP,[24] or work packages) not only sequential but sometimes overlapping (Fig. 1.5):

WP1) PART I, II (CH 1-2-3-4). Acquisition of preliminary information and definition of the state of the art, in which the subject of study is described constituting a basis bibliographic and "outlining the logic of the argument" (Booth et al., 2003), or explaining the arguments in support of the research objectives, also through the validation by expert interlocutors to refer to;

WP2) PART III (CH 5-6). Data collection phase, in which an information database deriving from the analysis of case studies was processed. This cognitive path served to define operational tools for applied research, "linking data to propositions" (Yin, 1981);

WP3) PART IV (CH 7). Instrumental-applicative phase, verified through a series of laboratory experiments which constitute the outputs supporting the doctoral thesis;

WP4) PART V (CH 8-9). Analytical phase of the research results through the systematization of the research areas explored, definition of potential practical applications and conclusive annotations on future implications.

The results of the research were made explicit (Cross, 2001) through applied experimentation. The application output was defined through hypotheses derived from the literature review and was validated through journalism (Groat and Wang, 2013), ie the analysis of the results and the revision of the assumptions. The different work packages were made communicable through publications in peer-reviewed scientific journals and participated in conferences. In this way, the body of knowledge generated in the three years has been disseminated and the results can be used in the context of academic research to contribute to the advancement of knowledge in the field of technological architecture design (Fig. 1.6).

23 Based on J.Creswell definition: "the qualitative approach in research seeks to establish the meaning of a phenomenon.
24 Work Packages, from H2020 terminology: https://ec.europa.eu/eurostat/cros/content/work-packages-0_en.

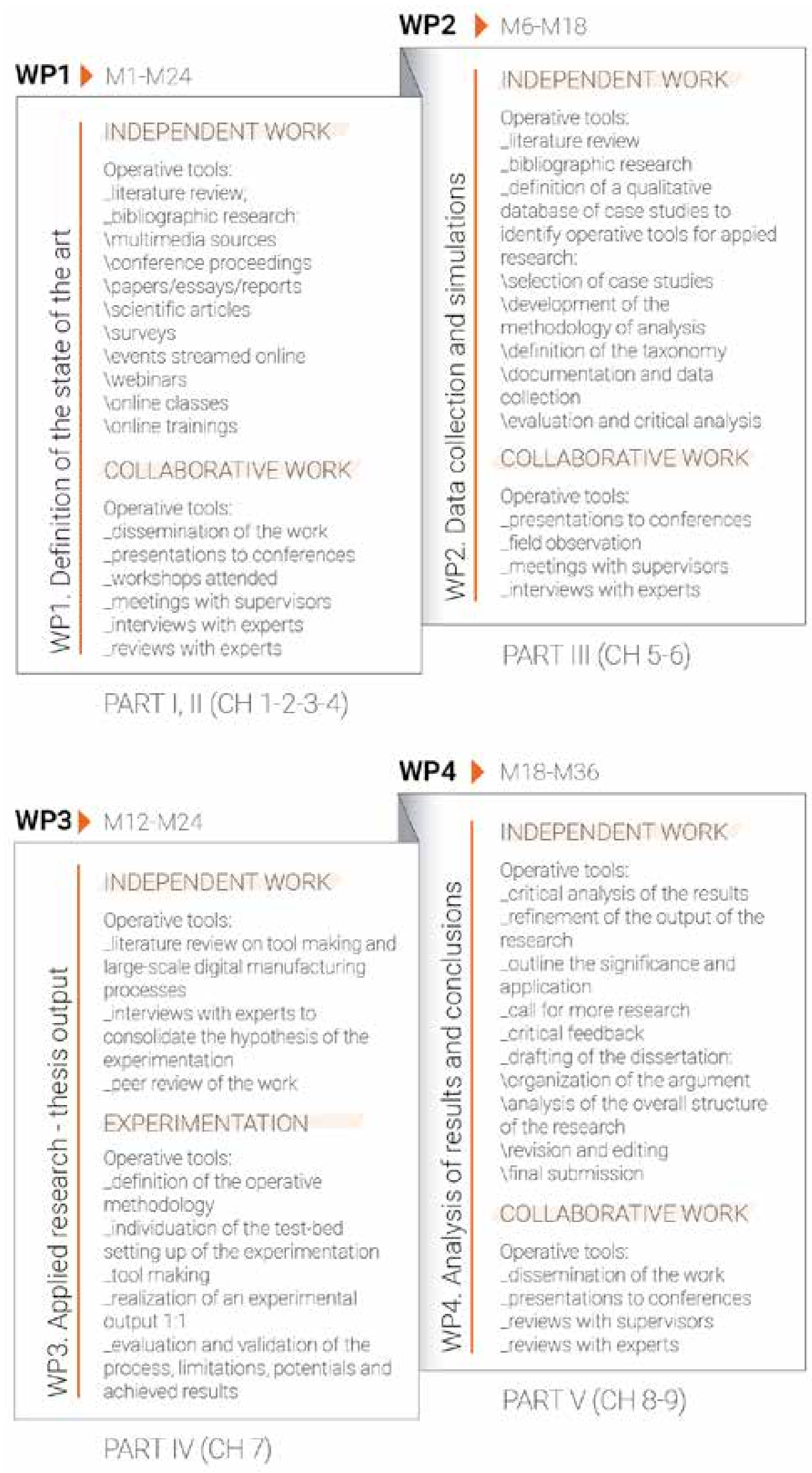


Fig. 1.5 Working packages of the research. The four phases carried out for the development of the dessertation.

WP1: Study of the state-of-the-art (M1-M36)

WP1 Research questions

- in the current scenario of affirmation of the digital transformation and of the Fourth Industrial Revolution, which design strategy allows to innovate the recovery site in terms of: safety in the processing, marginalization of result uncertainty and optimization of the use of material resources?
- which design strategy allow the architects not to lose their centrality and to be the element of dialogue between Architectural Heritage and fabrication-aware design?
- Is it possible to bring the methodologies of the heritage recovery site back to a digital strategy that allows inclusion in the early stage phase forecast aspects in the production of customized architectural units / components / systems through the processing of a digital twin?

WP1 Results

- study and analysis of the state of the art on the themes of digital transformation, the Fourth Industrial Revolution, and the respective innovative effects in the architecture and construction sector;
- focused the research field to a key topic by identifying the different theoretical currents, mainly national and European, which can open a dialogue in the academic research sector on possible application scenarios for Cultural Heritage;
- shrinking, with increasing precision, the framing of the scientific problem to the field of large-scale robotic ALM as a technology to be used on-site in relation to culturally relevant historical architectures;
- definition of a research question, to formulate an operational methodology that results in applied experimentation not already covered by previous research.

WP1 Operative tools

- establishment of the reference bibliography (following J.Creswell methodology, step 1: identifying the keywords, step 2: finding journals and books related to the topic, step 3: setting a priority on the search; step 4: narrowing those publications that is central to the topic; step 5: organizing a literature map; step 6: drafting summaries of the most relevant articles; step 7: organizing important concepts and addressing the study);
- direct comparison with thesis supervisors and industry experts to validate and consolidate research hypotheses;
- dissemination of the progress of knowledge on the state of the art and on the methodological approach to research, to obtain peer-reviewed feedback within the academic world and in particular from professors belonging to the scientific / disciplinary sector ICAR | 12.

Since the research field at the time of writing is exponentially evolving, the analysis of the state of the art has required a continuous updating during the course of the three doctoral years, ie from month 1 to month 36 (M1-M36).[25] The area of investigation has been outlined: starting from the general area

25 The abbreviations M- are typical of the research schedules of the proposals for European research projects. See the website of the European Commission: https://ec.europa.eu.

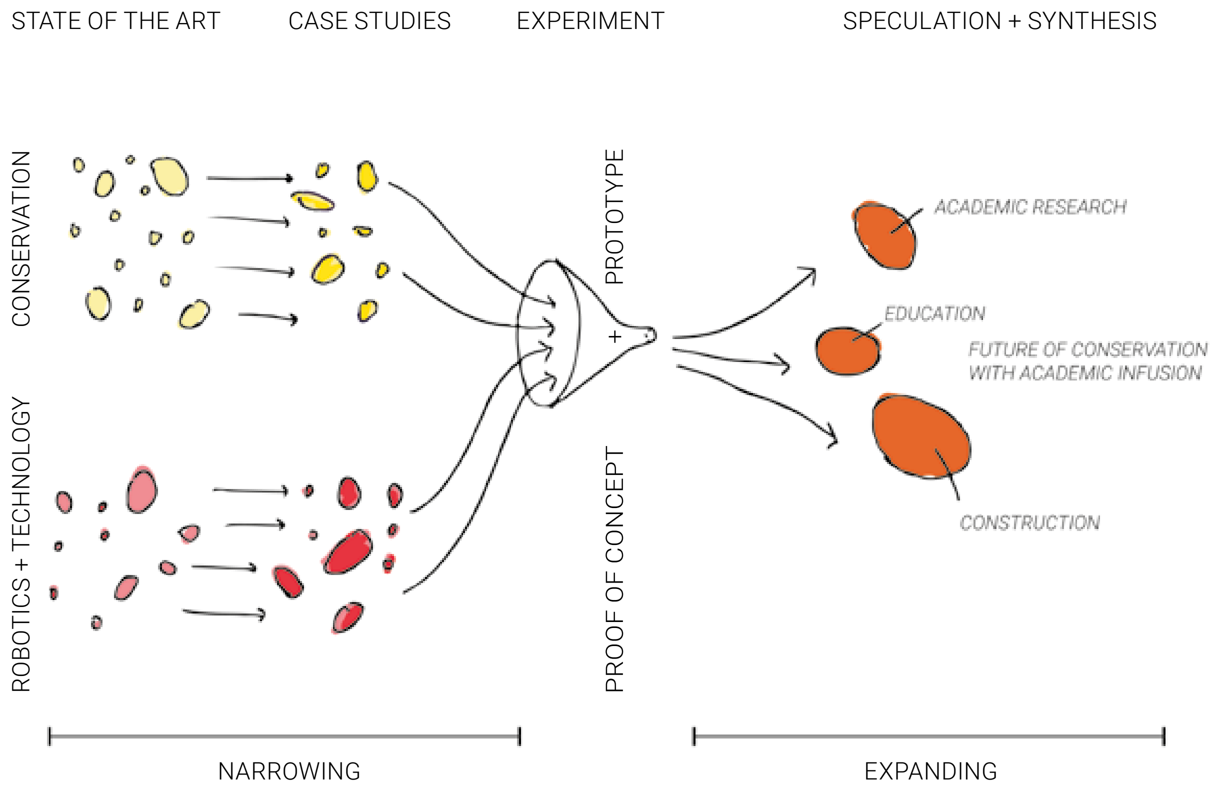


Fig. 1.6 Research methodology. This work has been carried out by adopting a case studies analysis approach. An applied application was defined to support the subject under study. The evaluation of results allowed to open the discussion and engage with different fields of knowledge.

of interest, to emerging technical innovations placed in the construction sector, and in particular in the construction / recovery processes. The main operational tool for this phase was the individual study, through which the information previously processed by other subjects was examined. This individual study occurred through the consultation of: bibliographic sources, scientific publications, multimedia sources, conference proceedings and papers published in national and international journals.

The individual study started with contributions of researchers at the home institution - University of Ferrara. The study of the state of the art followed the formulation of the research question, indispensable for the elaboration of an operational strategy to conduct research towards applied experimentation. The research question is linked to literature and "the methodological approach to research" or in other words "it determined too a large extent the research methods that are used to study it" (Strauss and Corbin, 1998). The formulation of the research question, in this study, took shape starting from the reading of future scenarios or open questions, expressed at the conclusion of ongoing relevant research. This approach has allowed the research to develop into two lines of research, the first concerning the design interventions on Cultural Heritage and the second concerning the cultural opening to digital technologies for managing the recovery process. Participation in the conferences at this stage was decisive in order to build a network of interlocutors to be able to compare and at the same time have access to updated information, well in advance of the publication of the proceedings. Several foreign institutions, universities and research centers were also visited, and seminars and workshops were held.

WP2: Data collection: selection of case studies and definition of operative tools (M6-M18)

WP2 Research questions

- among the technological systems studied, which of them contribute to expand the intelligence of the project and can be introduced in architectural and building practice?
- What are the application limits and what are the critical issues that prevent a consistent application of new technologies outside the experimental field and academic research?
- to which application scale is it optimal and advantageous to work with robotic instruments in architecture?

WP2 Results

- data collection on the main lines of investigation and elaboration of a database of qualitative information regarding application cases of 1)restoration of buildings of historical and architectural significance; 2) digital fabrication, with particular focus on industrial robots, for the creation of full-scale architectural technology units;
- management of the information collected in order to indicate potential for each project and technical criticality;
- targeting research towards an approach that combines automated production technologies and heritage based on results already achieved in the field of new construction;
- transposition of the critical points of the traditional construction site into operational sequences to be carried out hypothetically through the use of digital tools for survey, diagnostics, and manufacturing;
- identification of an order of priority for which the critical issues must also be resolved on a laboratory scale so that the technology can be used in the field;
- identification of an aspect that can be solved and set up an experimental hypothesis that can be used to contribute to the theoretical and technical discussion on international research tables.

WP2 Operative tools

- extension of bibliographic research in order to define a detailed information database through the study of papers, scientific publications and multimedia sources. Access to qualitative and quantitative data also took place through field observation, interviews with experts, and reviews of documents or records;
- selection of case studies in two areas of research and clarification of the logic that unites them;
- development of a case study analysis methodology;
- definition of the analysis taxonomy of the selected examples;
- collection of the material and documentation necessary to set up operational tools for the development of applied research;
- compilation of the analysis files and evaluation of the case studies;
- critical synthesis of case studies and clarification of the criteria for interpreting the findings;
- formulation of general and specific research questions to be answered through applied research.

The research continued through observation and investigating contemporary phenomenons in the real-world context in depth, that is building a selection of case studies at a national and international level describing the potential of the large-scale robotic ALM. For this research it was considered appropriate to carry out the analysis of case studies, taking as reference the classification carried out by Robert Yin, to a case study (Yin, 2017):

- "copes with the technically distinctive situation in which there will be many more variables of interest than data points";
- "benefits from the prior development of theoretical propositions to guide design, data collection and analysis";
- "relies on multiple sources of evidence".

The repertoire of experiences has involved on the one hand projects of restoration and on the other systems of units, technological sub-systems, or architectural systems created through digital workflows.[26] It was useful to define with precision the phases of the innovative manufacturing processes, the hardware and software components specially developed between the operators included in the process. The outliers were also excluded from the area of interest.

26 The case studies are listed and analyzed in Chapter 5. They are classified into the categories: 1) Cultural Heritage conservation and 2) Robotics. The latter, was also divided into a) Disembodied Craft and b) Computer Vision Systems.

WP3: Applied research: laboratory experimentation (M12-M24)

WP3 Research questions

- can digital fabrication technologies, especially robotic ALM, expand the design possibilities for customized production of architectural components?
- What are the tools through which the application of these technologies could become commonplace?
- What skills do industry professionals need to learn to take advantage of digital project workflows?

WP3 Results

- formulation of a theoretical hypothesis for the recovery and conservation of Cultural Heritage for which digital technologies are used for the phases of survey, diagnostics and digital fabrication;
- laboratory simulation of a construction process carried out using robotic instrumentation. Perimeter of the operational phase with focus on shortening the production chain of technological units, through large-scale robotic ALM;
- re-proposing a portion of a real test-bed in the laboratory;
- setting up a laboratory workflow aimed at investigating a construction site complexity that can occur during the interaction between robotics and existing surfaces;
- realization by means of additive manufacturing of a technological unit on a damaged architectural element by simulating an on-site robotic workcell and controlling the architectural image of the result;
- evaluation of the TRL;
- validation of compatibility between large-scale robotic ALM and interventions on existing buildings.

WP3 Operative tools

- literature review on tool making and processes of large-scale digital manufacturing;
- interviews with experts to strengthen the hypothesis of experimentation;
- dissemination of work in progress to make corrections by peer-reviewer experts in the field;
- definition of the operative methodology and verification of competences for a potential practical application;
- elaboration of the hypothesis of an experimental workflow;
- individuation of the test-bed;
- setting up of the experimentation, definition of mockups;
- tool making and programming;
- realization of an experimental output as a proof of concept, scale 1:1;
- comparison of the laboratory workflow carried out with the one assumed in the introduction;
- evaluation and validation of the process, clarification of limits, potential and results achieved.

The instrumental-applicative phase took place through a series of experiments that constitute the outputs in support and verification of the doctoral thesis. The output is configured as a proof of concept (TRL3). The applied research phase was carried out in the laboratories of the College of Architecture and Design of the Lawrence Technological University, between the second and third doctoral year with the title of Visiting Scholar. This phase has been exploited to investigate in first person the production and innovation processes of each phase of the process. In order to set up the practical experimentation, on the basis of the logical path previously expressed, it was essential to understand the skills necessary to carry out the laboratory activity. The bibliographic study was the starting point. The information was integrated through the field observation of experiments carried out at various research centers and directed comparisons with experienced interlocutors.

WP4: Analysis of results and conclusions (M18-M36)

WP4 Research questions

- which knowledge must be integrated, in the context of university academic research so that new professionals are able to design in the early stage phases according to fabrication-aware design strategies?
- how the experimental phases can be expanded?
- what are the lines of investigation that can be opened in the near future on the subject?

WP4 Results

- critical analysis of experimental results and research output, or the simulation of recovery intervention of a damaged architectural element through a digital workflow aimed at design and digital fabrication;
- definition of guidelines for refinement of experimentation, correction of certain technical inaccuracies;
- call for more research (Booth et al., 2003) through the elaboration of guidelines for the advancement of the TRL in the field of academic research by applying robot sensing, high engineered materials, and software and hardware customization;
- introduction of the concept of theoretical protocol for the definition of a structured research field that includes robotics and Architectural Heritage.

WP4 Operative tools

- drafting of the dissertation;
- organization of the argument;
- analysis of the overall structure of the research;
- revision and editing;
- final submission.

The final analytical phase was carried out by comparing the experimental output with the hypotheses posed in the premise of the work. The hypotheses were formulated before maturing the technical skills necessary for the realization of the output. This gave the opportunity to identify the skills that are useful to introduce in the field of higher education to prepare future generations of architects for future changes in the construction sector. All the information collected was structured for the preparation of the dissertation document. The writing took place on documents shared online with the reviewers in order to trigger a real-time feedback loop system that allowed continuous editing of text over iterations.[27]

27 WP1 is developed in PART I and PART II (Chapters 1-2-3-4). WP2 is developed in PART III (Chapters 5-6). WP3 is developed in PART IV (Chapter 7), WP4 is developed in PART V (Chapters 8-9).

1.6 Expected and achieved results

The two main objectives of the dissertation consist in the definition of:

1. **a hypothetical experimental workflow**
2. **a laboratory experiment to support the case**

Throught the case studies analysis it was possible to define a hypothetical workflow based on the theoretical knowledge. It was decided to address the research towards a technical application, to verify the applicability of large-scale robotics on a test-bed and learn from it. The selected test-bed is the Woodward Avenue Church, an abandoned building in Detroit classified as National Architectural Heritage. The experiment consisted in the simulation of a on-site construction process to use robotic additive layer manufacturing (RALM) to produce customized units for conservation. Using robots for conservation means working in a complex work-cell and interacting with existing volumes and irregular surfaces. The hypothetical workflow was validated through a first hand experiment. The applied research was carried out by adopting a low-budget-DIY strategy, with the support of a research team with a background in architecture and no previous exposure in robot programming. This activity allowed to inform the hyphothesis with the acquired technical knowledge.

The experiment successfully supported the case through the physical outcome. Only one iteration was possible. Further optimizations are proposed. The outcome is the result of:

- reproduction of a mock-up of the building's damaged element, in order to perform tests in lab;
- digital fabrication to produce an end-effector used to customize the production of an architectural unit to recover a damaged building;
- robot scripting by using algorithmic computing;
- CAD/CAM through an additive construction process within geometrical constraints on irregular surfaces.

Since it was an experimental activity, the Technology Readiness Level, TRL, scale was taken into reference. The experiments pushed TRL3 towards TRL4. Due to budget and skills limitations, it was defined as a MVP, minimum viable process.

The experiment allows for the reflection on the future of the restoration discipline in a systematic way from the point of view of theoretical reasons and in a technical way with the realization on a 1: 1 scale of a technology unit in a low-risk context. The realization served to promote a culture of a simulated industrialized restoration project, where the robots were able to perform repetitions but without the limits imposed by standardization and modularity.

The MVP / prototype of workflow could be replicated, deployed in different contexts, and transformed as appropriate. The results of the experiment are an opportunity to initiate a much broader discussion, which includes:

- higher-ed to prepare the architects of the future;
- the role of data-informed architects / digital master-builders to operate with new workflows for conservation;
- academic research, as a starting point to analyze how to scale-up processes;
- future trends and innovation within the construction industry.

1.7 Collocation of the scientific research in the area of architectural technology

This research work expresses a multidisciplinary and multi-scale approach that aims to launch a debate between two specialized subject areas:

- process innovation, product planning, and execution of architectural practice;
- conservation and recovery of Architectural Heritage.

The field of exchange between these research areas consists of the digital infrastructure that constitutes the common language through which the professionals of the supply chain interface in the early stage decision-making phases. The digital revolution has already established itself in the design phases on the one hand as a result of a process started in the nineties and in the phases of geometric survey, survey of degradation and diagnostics on the other. The current affirmation of the Fourth Industrial Revolution brings production tools closer to design. This operational opportunity allows for the start a methodological reflection on the creative and constructive process in order to understand the changes taking place and their impact not only in the design of new buildings but also in the built environment. In fact, both disciplines can benefit from the constant evolution of digital acquisition tools and production tools, given the evolution of materials and construction technologies. Given the issues discussed and the experimental survey conducted, despite the interdisciplinary nature, the research is in the scientific disciplinary area 08:[28] civil engineering and architecture. The areas are altogether fourteen and are used by Italian university bodies to organize higher education. With respect to the disciplinary area, the thesis refers to the 08 / C macro-sector - Design and Technological Design of Architecture and in turn to the scientific disciplinary sector (SSD) ICAR / 12[29] - Technology of Architecture. This study is therefore addressed to the SITdA - The Italian Society of Architectural Technology[30] and in particular to the thematic clusters[31] proposed by it:

- production / building product;[32]
- Architectural Heritage.[33]

The clusters represent research networks formed by an articulated series of interdisciplinary skills, which SITdA Members have developed over time. Through the clusters, the SITdA provides a series of specific and interdisciplinary skills that can assist the operators in the building sector in proposing adequate design, implementation and management solutions.

28 A first grouping of the thematic areas was established in 1973 (DL 1 October 1973, n. 580 - Urgent measures for the University), converted into L. 766/1973). The current sectors are established by the ministerial decree 30 October 2015, n. 855 and are effective from November 20, 2015, date of publication in the *Official Journal of the Italian Republic*.

29 Ingegneria Civile ARchitettura (Icar): http://www.miur.it/UserFiles/115.htm.

30 SITdA, Italian Society of Technology of Architecture: http://www.sitda.net/home-eng.html.

31 SITdA Clusters: http://www.sitda.net/cluster-eng.html.

32 Building product / production: http://www.sitda.net/cluster-eng/production-building-product.html.

33 Architectural Heritage, SITdA cluster: http://www.sitda.net/cluster-eng/architectural-heritage.html.

Although the thesis proposes a design and operational methodology in reference to a specific application field (large-scale robotic ALM and Architectural Heritage), its content can be traced back to the deepening of the following issues related to SITdA research clusters:

- reliability of processes, with application of performance approach to support the different decision-making phases;
- product innovation, in many cases transferred from the industrial sector, in which a fundamental role is determined by the new performance of materials and construction techniques and by the evolution of new information tools for the project;
- process innovation, in which there is an exponential growth in the role of production within construction processes, as well as a complexity and multidisciplinary nature of the management of construction, organizational, methodological and evaluation procedures;
- changes in architectural languages, connected to the culture of building;
- material and immaterial accessibility to Cultural Heritage;
- ICT application, Information Communication Technologies, BIM and algorithmic-generative design forms.

1.8 Audience and post-doctoral developments of the research

The thesis represents a critical application of an emerging construction technology. The specific choice to investigate a production technology of additive manufacturing and to explore a hypothesis of on-site intervention is part of a vastness of possible applications. The robotics sector, especially with regard to on-site operating methods, today lacks a regulatory organization structured at national and European levels. If the high-engineered tools and materials are today certified or undergoing certification, there are no guidelines to regulate their applications, for example in terms of site safety. This investigative work is not mature enough to be able to address directly the architects' concerns, although the architects will represent the actual final recipients of this research path in the future. Data will represent an innovative component in future workflows and will be entrusted to the professionals in the initial decision-making phase. This data-rich workflow will be supported by AI and machine learning to optimize the processes. The continuation of the research work may involve stakeholders such as:

- universities;
- research centers;
- academic spinoffs;
- start-ups;
- industries operating in the development of technological systems for architecture.

Academic research is fundamental. From the point of view of university research, a series of possible investigations emerge which may have repercussions at different scales of analysis and depending on the technology adopted. This research has the potential to spread knowledge methodically so that the technique doesn't prevail over the cultural aspects of the architectural project. This again highlights the need for a critical approach for the protection of interventions on existing buildings that are culturally relevant.

A possibility to continue the research is by collecting the results of this work and set up an experimental follow-up to make the outcome more sophisticated in terms of environmental, structural, spatial and material performance. In order for this to be possible, it is necessary to broaden the range of skills of researchers and extend the involvement of the project to experts in materials science, software programming, and hardware development. In fact, there are many aspects that have remained incomplete and unresolved in laboratory activities that are worthy of further study. One of these is the use of a low-engineered material that has limited the analysis of the static, energy and cost performances of the architectural component realized through robotic ALM. In this regard, it is proposed to cultivate the collaboration between the Department of Architecture of the University of Ferrara with the College of Architecture and Design (LTU), with the technical support of Ballard International[34] to continue the applied research started during the doctoral period.

Further possibilities are given by the potential use of knowledge on the thematic areas that the thesis deals with to participate in the assignment of European ERC funds and to start partnerships within the framework programs promoted by the European Commission. Innovations in the building production sector with a focus on heritage are already of particular interest in the Horizon 2020 calls, in the calls for tenders RI (Innovation Actions), RIA (Research and Innovation Actions), and FET (Future and Emerging Technologies). Current investments by companies in AI and machine learning for the purpose of human-machine collaboration in the construction sector suggest that many of the upcoming research grants will leave space for research on application fields of smart robotics.

As for the industrial environment, there are already examples of companies[35] that are investing in the development of automation tools to relocate robots from the factory and take them to the construction site. A further step that will be indispensable to carry out for the operability of these technologies will be to put robots in communication through a common interface. The needs of the recovery site in fact presuppose the on-site presence of several industrial machines which must be put in a position to monitor the work space, analyze the data collected and process the operational information. Following the example of the robotic interface launched on the market by the Formant company[36], the market demand for platforms for remote management of the digital construction site will be formulated, from pre-construction simulations to post-construction checks.

The start-up experience is also mentioned for the spread on the mass market as customized houses Blu Homes, for the development of additive manufacturing technologies as XtreeE[37], and Branch

34 Ballard International: https://ballardintl.com/.
35 Examples are: CAT, Skanska, Kuka, Fanuc, and ABB robotics.
36 Formant: https://formant.io/.
37 XtreeE: https://www.xtreee.eu/.

Technology,[38] and the development of the mobile robots for productivity as HarvestAutomation,[39] Capsen Robotics,[40] and Rethink Robotics.[41] The contents of this thesis can be useful material for founding a start-up to initiate an experimentation process that transfers innovative processes and methodologies into professional practice. The ambition could be to specialize in the development of a technological specification and then be absorbed by larger and more structured research organizations. This was the case of Bot & Dolly[42] absorbed by Google or Kinema Systems acquired by Boston Dynamics. The benefit of leveraging this research into a start-up lies in the potential of involving researchers and construction companies in a multidisciplinary consortium. This work can then define alternative operating and business models to those of the traditional construction site that are destined to be left behind in the disruptions of a first world economy. With the same logic, the contents of the thesis can be used in the framework of an academic spin-off, for the realization of patents and new technological systems.

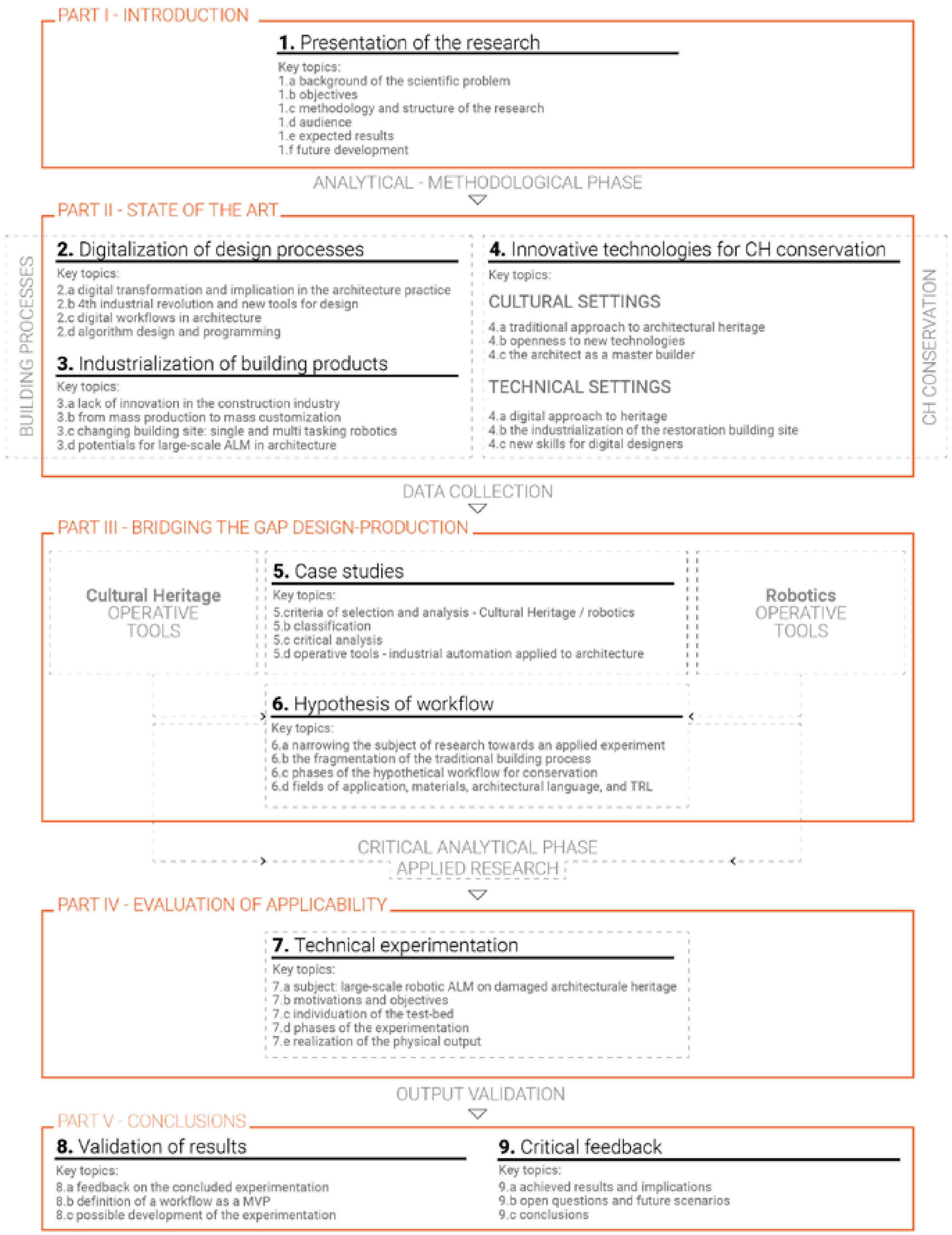
Finally, the acquired knowledge is also a resource that requires a reflection on the current university educational offerings, in particular at the DA-unife home institution. From a technical point of view, the themes touched on by the thesis were the following:

- algorithmic design and programming;
- desktop digital fabrication;
- large-scale robotic digital fabrication;
- additive manufacturing.

None of these aspects are present today in the formative course offerings of the University of Ferrara. This, despite the market needs indicate that there is a growing demand for professionals who are able to operate using the digital tools mentioned above. Therefore it is the intention of this thesis to make the home institution research centers aware of these issues, in view of a possible update of the training curriculum so that outgoing students are more competitive on the quickly evolving market. To start this process we intend to introduce the approach to the Robotics in Architecture theme through collateral courses to define in which year of the course and with which modality to effectively insert the ingredients for a new design culture.

38 Branch Technology: https://www.branch.technology/.
39 Harvest automation: https://www.public.harvestai.com/.
40 Capsen Robotics: http://www.capsenrobotics.com/about.html.
41 Rethink Robotics: https://www.rethinkrobotics.com/.
42 Bot & Dolly: https://www.bloomberg.com/news/articles/2014-03-20/bot-and-dolly-and-the-rise-of-creative-robots.

1.9 Structure of the research



1.10 List of frequently used abbreviations

0

3DP: 3D Printing.

A

A1-A2-A3-A4-A5-A6: Kuka kr6-arc axis.
ABS: Acrylonitrile Butadiene Styrene. It is a common thermoplastic well known in the injection molding industry.
AEC: architecture engineering and construction.
AH: Architectural Heritage.
AI: artificial intelligence.
AIA: American Institute of Architects.
AM: additive manufacturing.
ALM: additive layer manufacturing.
AR: augmented reality.
ASTM: American Society for Testing and Materials.

B

BEM: building energy modelling.
BIM: building information modelling.
Brep: Boundary Representation.

C

CAD: computer aided design.
CAM: computer aided manufacturing.
CFab: cellular fabrication.
CH: Cultural Heritage.
CI: collaborative intelligence.
CoAD: College of Architecture and Design.
CSP: cyber-physical systems.

D

DDD: data driven design.
DH: digital humanities.
DIY: do it yourself.
DM: direct modelling.
Dx: Digital Transformation.

E

EPFL: Ecole Polytechnique Fédérale de Lausanne.
ETH Zurich: Eidgenössische Technische Hochschule Zürich.

F

FabLab: fabrication laboratory.

FDM: fused deposition modeling. It is an additive manufacturing process that uses a continuous filament of a thermoplastic material.
FFF: fused filament fabrication (sometimes called filament freeform fabrication). It is an additive manufacturing process also known under the trademarked term FDM.
FRP: fiber reinforced polymers.

H

H2020: Horizon2020.
Harvard GSD: Harvard Graduate School of Design.
HBIM: Historic Building Information Modelling.

I

IAAC Barcelona: Institute for Advanced Architecture of Catalonia in Barcelona.
ICAR: Ingegneria Civile ARchitettura.
ICD Stuttgart: Institute for Computational Design in Stuttgart.
ICCORM: International Centre for the Study of the Preservation and Restoration of Cultural Property.
ICOMOS: International Council on Monuments and Sites.
ICOM-CC: Committee for Conservation of the International Council of Museums.
ICOM: International Council of Museums.
ICR: Istituto Centrale Restauro (Central Institute for Restoration).
IDA. Institute of Digital Archaeology.

K

Kuka Prc: Kuka Procedural Robot Control.

L

LIN move: linear kinematics.
LOD: level of detail.
LTU CoAD: Lawrence Technological University, College of Architecture and Design in Southfield, MI.

M

MIT: Massachusetts Institute of Technology.
ML: machine learning.
MVP: minimum viable product / process.

N

NRHP: National Register of Historic Places (U.S. National Park Service).

O

OCR: optical character recognition.

P

PLA: Polylactic Acid. It is a thermoplastic derived from renewable resources such as corn starch or sugarcane. It is commonly used for desktop FDM additive manufacturing.
PTP move: point-to-point kinematic.

R

RALM: robotic additive layer manufacturing.
RAM: robotic additive manufacturing.
READ: Recognition and Enrichment of Archival Documents project.
RHWC: Robotic Hotwire Cutting.
Rob|Arch: Robotics in Architecture, Art, and Design.
RPAS: Remotely Piloted Aircraft Systems.
RSID: Ryerson University - School of Interior Design.

S

SITdA: Italian Society of Technology of Architecture.
SPL move: spline kinematics.
SRL: systems readiness level.
STL: stereolithography.

T

TCP: tool center point.
TLS: terrestrial laser scanning.
ToA: technology of architecture.
TP: teach pendant.
TRL: technology readiness level.

U

UCL Bartlett: The Bartlett University College London.
UNESCO: United Nations Educational, Scientific and Cultural Organization.
UNSW Sydney: University of New South Wales in Sydney.
UoM: University of Michigan, Taubman College in Ann Arbor.
UoT: University of Toronto.

V

VR: virtual reality.
VTM: Venice time machine.

W

WP: working package.

1.11 Peer-reviewed dissemination of the research

CHAPTER 2

Title: Definition of innovative material scenarios through digitization processes.
Author(s): Sara Codarin and Marco Medici.
Typology: paper in journal.
Journal title: TECHNE (ANVUR - GEV 08 - Scientific Journal, Class A VQR).
Pages: 308-316.
Date: 2018.
Journal affiliation: Firenze University Press.
Peer-review: double blind.
Relevance: international.

Title: Digitizing the Building Site for Restoration Projects: From ALM Technologies to Innovative Material Scenarios.
Author(s): Sara Codarin and Marco Medici.
Typology: proceedings of international conference.
Title of the conference: Euro-Mediterranean Conference 2018.
Pages: 718–727.
Date: 2018.
Journal affiliation: Springer Lecture Notes in Computer Science.
Peer-review: double blind.
Relevance: international.

Title: Progettazione digitale e prototipazione rapida in architettura. Modellazione parametrica e Additive Layer Manufacturing come strumenti per la definizione di un nuovo paradigma progettuale.
Author(s): Sara Codarin (single author).
Typology: proceedings of national conference.
Title of the conference: VI Forum ProArch. La domanda di architettura. La risposta di progetto.
Pages: 162-165.
Date: 2017.
Journal affiliation: Collana della società ProArch.
Peer-review: acceptance by the scientific committee.
Relevance: national (IT).

CHAPTER 3

Title: Metodologie innovative nei processi di costruzione tra genius loci e globalizzazione.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Ufficio Tecnico.
Pages: 8-16.
Date: 2016.
Journal affiliation: Maggioli editore.
Peer-review: acceptance by the scientific committee.
Relevance: national (IT).

Title: Progettazione digitale e additive layer manufacturing. L'uso di tecnologie innovative di modellazione parametrica e prototipazione rapida in architettura.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Officina*.
Pages: 10-11.
Date: 2018.
Journal affiliation: Editore incipit srl.
Peer-review: double blind.
Relevance: national (IT).

Abstract accepted at Sitda - International conference Design in the Digital Age. Technology, Nature, Culture - Naples, 25-26 june 2020. See: http://www.sitda.net/naples2020/.

CHAPTER 4

Title: The Conservation of Cultural Heritage in Conditions of Risk, with 3D Printing on the Architectural Scale.
Author(s): Sara Codarin (single author).
Typology: proceedings of international conference.
Title of the conference: ITN-DCH Final Conference - Digital Cultural Heritage.
Pages: 239-256.
Date: 2018.
Journal affiliation: Springer.
Peer-review: double blind.
Relevance: international.

Title: Processi innovativi di conservazione e recupero del patrimonio culturale.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Ufficio Tecnico.
Pages: 12-21.
Date: 2016.
Journal affiliation: Maggioli editore.
Peer-review: acceptance by the scientific committee.
Relevance: national (IT).

CHAPTER 5

Title: Tecnologie di stampa 3D. L'applicazione per la valorizzazione del patrimonio culturale.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Recupero e Conservazione.
Pages: 33-50.
Date: 2017.
Journal affiliation: Rec. editrice.
Peer-review: acceptance by the scientific committee.
Relevance: national (IT).

CHAPTER 6

Title: Innovative technologies for the recovery of the Architectural Heritage by 3D printing processes.
Author(s): Sara Codarin, Marta Calzolari, and Pietromaria Davoli.
Typology: proceedings of international conference.
Title of the conference: XXXIII Convegno Internazionale 2017 Scienza e Beni Culturali - Le Nuove Frontiere Del Restauro.
Pages: 669–680.
Date: 2017.
Journal affiliation: Edizioni ACADIA Ricerche - Trasferimenti, Contaminazioni, Ibridazioni.
Peer-review: acceptance by the scientific committee.
Relevance: international.

Title: Digital Manufacturing and Cultural Heritage. An experimental workflow for the digitization of restoration processes.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Recupero e Conservazione.
Pages: 40-47.
Date: 2019.
Journal affiliation: Rec. editrice.
Peer-review: acceptance by the scientific committee.
Relevance: national (IT).

CHAPTER 7

Title: Additive manufacturing. The technologies of layers interventions and the Cultural Heritage of the built environment.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Cubic Journal.
Date: 2019.
Journal affiliation: University of Hong Kong.
Peer-review: double blind.
Relevance: international.

Title: Digital Manufacturing and Cultural Heritage. Interazione tra sistemi robotici automatizzati e contesti geometrici complessi a scala architettonica.
Author(s): Sara Codarin (single author).
Typology: paper in journal.
Journal title: Recupero e Conservazione.
Pages: 61-67.
Date: 2019.
Journal affiliation: Rec. editrice.
Peer-review: acceptance by the scientific committee.
Relevance: national (IT).

CHAPTER 8

Abstract accepted at ACSA - ARCH Annual Meeting Committee. Cathegory Digital Technology. See: https://www.acsa-arch.org/conference/108th-annual-meeting/.

CHAPTER 9

Abstract accepted at: Cumulus conference - Design Culture(s), June 16-19 2020, Rome. See: https://cumulusroma2020.org/.

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PART II - STATE OF THE ART IN ROBOTICS

2 The digitalization of building processes

ABSTRACT

The chapter explores the technological shift that is occurring in the design field. Technology is a force that is changing contemporary culture with consequences in economics, education, work, and manufacturing. These changes started having a global impact in the 2010s, when the ubiquity of mobile internet, the increase in computing power, the availability of vast amount of data, the spread of robotics and sensors, and the advancement of machine learning gave rise to the Fourth Industrial Revolution. It consists of fluid interactions across digital and physical realms. In this framework, designers have the opportunity to access new tools through which to expand the creative possibilities and enable the customization of products as an expression of the post-industrial era.

Computational design, additive manufacturing, materials engineering paves the way for new workflows and new operating models. The typical tools of the Fourth Industrial Revolution are emerging from the productive context of the economy of scale and allow architects to compress the distance between designers and builders. Robotics and digital fabrication can materialize the digital space in flexible ways and allow conceiving and making at the same time without a clear separation between these two operations. The logic of digital tools allows for the conflation of project generation, project description, and materialization. Design and manufacturing take place almost at the same time as the two processes are developed using the same tool, that is the computer.

The evolution of industrial technology has changed the way of mass producing and therefore also the way of producing architecture. By focusing on Architectural Heritage, it is possible to examine how industrial revolutions in conservation have been affected. With reference to the field of existing interventions, architects express themselves through a digital language to reduce project uncertainties and ensure greater awareness in operational choices. Awareness is even more necessary for work on heritage, historically the result of a sedimentation of techniques acquired by craftspeople, which requires non-standard solutions to be defined on a case by case basis.

The chapter concludes with a practical application of algorithmic design and digital fabrication through a design workshop held during the doctoral period.

Keywords: *Digitalization, Fourth Industrial Revolution, Second Digital Turn, Parametric Design, Algorithms*

2.1 The Fourth Industrial Revolution and the role of digital tools in construction

"It is the science of calculation which becomes continually more necessary at each step of our progress, and which must ultimately govern the whole of the applications of science to the arts of life [Charles Babbage, 1832]

In 2011, within the *Hannover Fair* event,[1] the term Industry 4.0 was introduced for the first time[2], to describe an ongoing global change dictated by connectivity and automation of production tools. The systematization of these elements contributes to the definition of smart factories, within which the manufacturing takes place by fluidly and flexibly processing data between the physical and digital worlds. In order for this information exchange to take place, the machines are enriched with a cognitive autonomy, defined as cyber-physical system - CSP[3] (Lee, 2008). In 2014, Erik Brynjolfsson and Andrew McAfee formalize the new era in which machines become more integrated and sophisticated with the definition the Second Machine Age (Brynjolfsson and McAfee, 2014). It is considered the time when digital technologies are mature enough to generate global social and economic changes.

In 2015, Klaus Schwab, chair of the *World Economic Forum*,[4] with an article in *Foreign Affairs* introduces the concept of The Fourth Industrial Revolution, or to wider condition where "fusion of technologies is blurring the lines between the physical, digital, and biological spheres".[5] This definition is predominantly used to refer to that force of change in contemporary culture that is exponentially evolving with consequences in economics, education, and work, with a big impact on manufacturing (Fig. 2.1). In his book *The Fourth Industrial Revolution*, Klaus Schwab explains the steps that led to this global state which is "faster than all others" (Schwab, 2017), in relation to the spread of digital technologies.

1 *Hannover Fair* event: https://www.hannovermesse.de/.
2 "The Industry 4.0 term first appeared at Hannover Messe in 2011 when Professor Wolfgang Wahlster, Director and CEO of the German Research Center for Artificial Intelligence, addressed the opening ceremony audience. The context of the term usage was how to be successful in a high region with global competition. He suggested that we should be in shape for the Fourth Industrial Revolution that is being driven by the Internet". See: https://www.automation.com/automation-news/article/the-4th-industrial-revolution-industry-40-unfolding-at-hannover-messe-2014.
3 Cyber-physical systems: https://www.sogeti.com/globalassets/global/special/sogeti-things3en.pdf.
4 *World Economic Forum*: https://www.weforum.org/.
5 The Fourth Industrial Revolution: https://www.foreignaffairs.com/articles/2015-12-12/fourth-industrial-revolution.

Starting from the moment when there was a transition from foraging to farming with the domestication of animals, about 10,000 years ago, humans shifted their way of living by producing food and enlarging their settlements. This led to the local growth of the population and the birth of cities through the first attempts at urbanization. It is in the cities that the first industrial revolution took place. It was not until the 1760's that muscle power was transformed into mechanical power through the invention of the steam engine. It also took 120 years before it spread outside Europe. Between the end of the nineteenth and the beginning of the twentieth century, the advent of electricity laid the foundations for the structuring of assembly lines that started mass production and the consequent economy of scale. As Schwab recalls, "it has yet to be fully exploited by 17% of the world, which lack access to electricity" (Schwab, 2017). Subsequently, with the entry into the computer market in the 1960's, personal computers in the 1970's and 1980's and the introduction of the internet in the 1990's came to create a digital ecosystem that pushed toward the Third Industrial Revolution, which "has yet to be fully exploited by 50% of the world, lacking internet access" (Schwab, 2017).

In the 2010's, the integration between the ubiquity of mobile internet, the increase in computing power, the availability of vast amount of data, the democratization of automated means of production, the development of sophisticated sensors, AI and machine learning gave rise to the Fourth Industrial Revolution, consisting of fluid interactions across digital and physical realms. This revolution has dictated the supremacy of digital business, which operating through digital platforms, "have reduced the marginal cost derived from transactions for the production of products, goods, or services" (Rifkin, 2014). In the context of the digital revolution, it was significant to see the transformation of the internet in relation to the means of production.

The world quickly went from the non-standard seriality of the static, read only web 1.0, to the collective intelligence of the web 2.0 of the late 1990's, to the semantic web 3.0 of the early 2000's, up to web 4.0, able to connect all devices in the real and virtual world in real-time. Connectivity 4.0 allows machines to communicate with each other through open networks and semantic descriptions. This machine to machine communication, or M2M, enables intelligent robots and computers to self-program and find optimal solutions (Wu et al., 2011).

In this framework, designers have the opportunity to access new physical and digital tools through which to expand the creative possibilities and enable the customization of products as an expression of the post-industrial and post-Fordist era.[6] Computational design, additive manufacturing, materials engineering paves the way for new workflows and new operating models. The interaction between voxel[7] and pixel is enabled by the internet of things (Ashton, 2009), whereby physical objects are connected to each other with sensors programmed through digital interfaces. These sensors are increasing in quantity as their prices continue to drop.

6 Mario Carpo in *Graz Architecture Magazine*: "Old Masters" (smokestacks, assembly lines, and strong trade-unions). For many of them, nonstandard simply meant the end of Fordism, hence by necessity the decline of trade unions; and they instinctively resented all things digital as the Trojan horse of neo-capitalism and neoliberalism".
7 Voxel in the Gartner dictionary: https://www.gartner.com/en/information-technology/glossary/volumetric-displays.

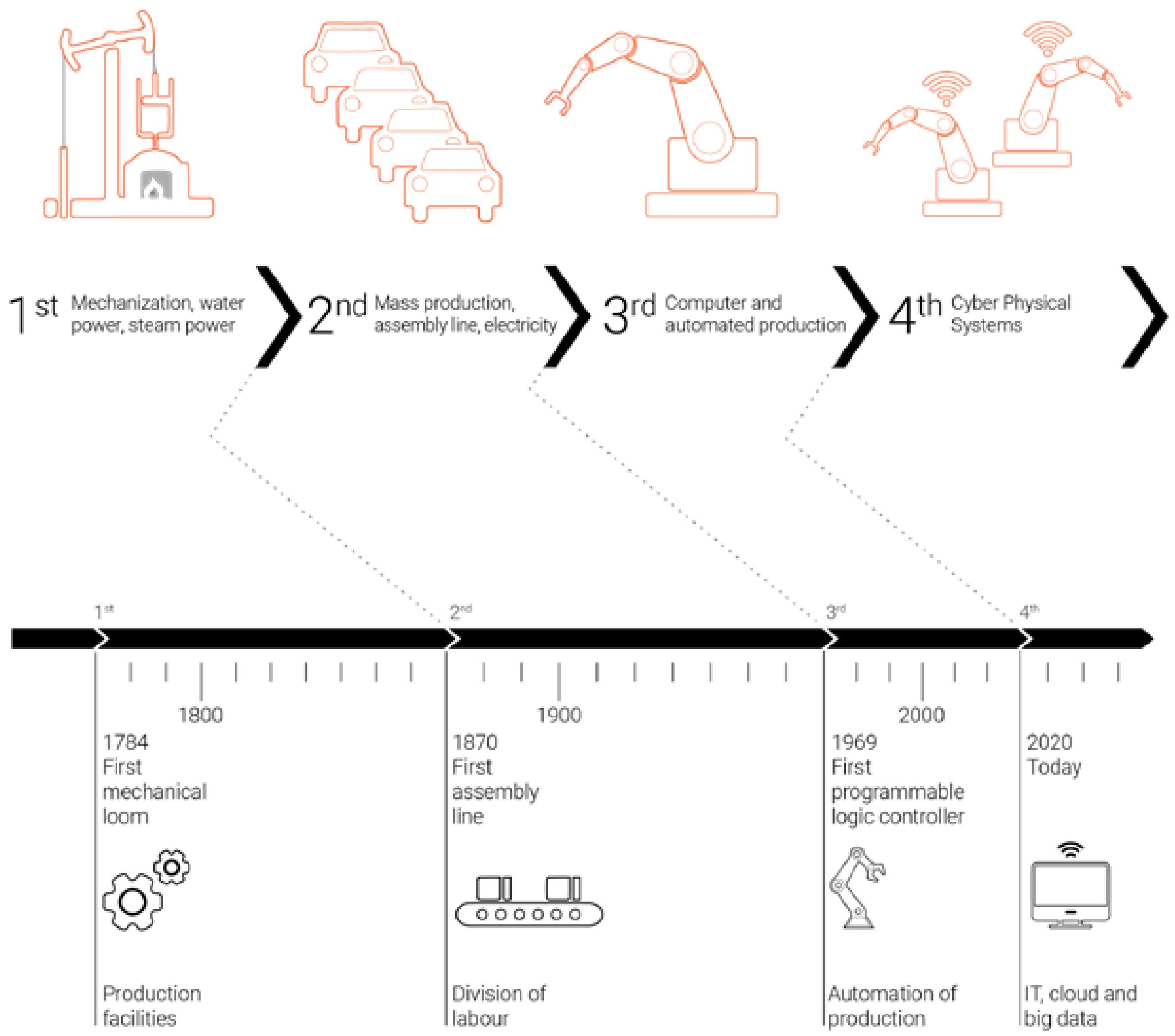


Fig. 2.1 Industrial revolutions across history: first (1760-1840), second (late 19th century - early 20th century), third (1960's), and fourth (present ages). Source: https://www.triple-c.at/ and "Pivoting Higher Education in the Fourth Industrial Revolution" in *The Daily Star.*

The material innovations that represent a potential for the construction sector are given by:

- autonomous vehicles, ie drones, aircraft, trucks that can integrate the operations that take place on-site, assisted by sensors and AI;
- additive manufacturing, a technology already explored in the automotive, aerospace, and medical industry sectors that allows exploring the shape without geometric limitations and opening up the search for customized solutions. The research on additive manufacturing is strongly influenced by the use of smart materials, able to insert the adaptive / responsive component capable of responding to environmental stimuli such as humidity or light factor (4D printing). Such materials, for instance having a memory that reverts to their original shapes after a change occurs;
- robotics, whose progress will increasingly lead to the generation of machines able to understand their surrounding environment, able to collaborate with humans, and to engage in a wide variety of complex tasks;
- new materials, lighter and stronger, sustainable, recyclable, composite, and adaptive.

2.2 Consequences in architecture

2.2.1 The Second Digital Turn

The First Digital Revolution, of the early 1990's, was the entry into the architecture of digital tools arriving from the aerospace and aeronautics sectors. This revolution happened at a time when architecture criticism was still busy formalizing deconstructionism, in the works of Zaha Hadid, Frank Gehry, and Peter Eisenman. Digitization favored the creation of new formal languages, "the new digital style of smoothy and curvy," spliny "lines and surfaces [...] now called parametricism" (Carpo, 2017). In this context the generation of forms could take place in a virtual environment through two and three-dimensional simulations as the product of a creative-interpretative act, a knowledge contribution of the element being designed. The possibility of generating formal and material simulations in a virtual environment comes from the First Digital Revolution (Carpo, 2013). In the last decade, we have witnessed the development of automated tools (robotic arms, extruders, 3D printers) capable of materializing the digital space in flexible ways, compared to the limits imposed by standardized production methods. This design context has been theorized by Mario Carpo as the Second Digital Turn (Carpo, 2013).

The typical tools of the Fourth Industrial Revolution are emerging from the productive context of the economy of scale and allow architects to compress the distance between designers and builders. Robotics and digital fabrication allow conceiving and making at the same time without a clear separation between these two operations. The role of the architect, inherited from the Renaissance, coincides with the separation between thinkers and makers, and is transformed because of the CAD-CAM relationship. The logic of digital tools allows for the conflation of project generation, project description, and materialization. Design and manufacturing take place almost at the same time as the two processes are developed using the same tool, that is the computer. From this point of view, "in a sense, the use of a computer is more medieval than modern",[8] which allows to simultaneously manage dimensional, geometric, numerical, and static information. In the Middle Ages the master-builder was the person able to make these decisions day after day on the construction site. This approach was taken up by Gaudì at the turn of the 1800's and 1900's for the construction of the Sagrada Familia. Gaudì, for his faith and his belief, tried to revive the designer-maker who did not draw but gave information to the makers through diagrammatic information or scale models.[9] This was an enterprise incompatible with industrial Barcelona at the beginning of the twentieth century, so much so that the use of digital fabrication is necessary in order to complete the ongoing project.[10]

Mario Carpo's vision is the one most shared by the scientific community. In his publications, he recalls how it was Leon Battista Alberti who handed down the idea that architectural production should be expressed with drawings and then let the builders make an identical copy in reality. The principle of architectural authorship is therefore inherent in its representation and becomes concrete once the geometric annotation is transferred to the physical world through translational, construction work. During the international 2017 *Fabricate* conference, Mario Carpo emphasized: "and I go back to the medieval and pre-notational way of thinking and making time - this is what we call digital craft, which is why I think we are much closer to the way we made physical things 500 or 600 years ago. We are reviving a pre-Renaissance, pre-Albertian, pre-Brunelleschian[11] way of making. [...] Where the master-builders were members of guilds, who conceive and make at the same time. [...] Paradoxically, we are returning to this " (Menges et al., 2017).

Process simulation has opened up new exploratory possibilities that are no longer closely linked to the traditional scientific method. Simulation is instead based on the observation of deterministic phenomena. The simulation of processes, tools, and materials in the digital world makes it possible to make predictions that are not necessarily based on the understanding of precedents. By informing machines (machine learning) with the rules to be respected and the principles to be followed, computers can formulate a large number of hypotheses until the most suitable or advantageous one is defined. Unlike the artisan who makes mistakes and goes over the design process several times, computers can afford to proceed exponentially faster by attempts: "thanks to the number-crunching power of computers, that exceeds that of humans by doing, and digitally controlled machines capable of performing a sequence of different actions, "the complexity of structural elements can increase exponentially" (Bonwetsch et al., 2010).

8 Mario Carpo, The Second Digital Turn, Talks at Google: https://www.youtube.com/watch?v=UVerq5DSdKU.
9 The most symbolic is the hanging chain model that was used to explain to the craftspeople the course of the forces of the arch systems that he intended to build. In this way he could help untrained people to understand very complex technical aspects that govern the buildings of his conception.
10 The completion of the Sagrada Familia is scheduled for 2026.
11 Mario Carpo in *Fabricate*: "Brunelleschi wanted to have the building built according to his ideas, but he didn't want to make drawings. He wanted to keep his ideas as secret as possible. He still had the mentality of a medieval craftsman. He was a goldsmith by training. We don't know how he built the dome".

The generation of non-deterministic predictive models allows for the theorization in the post-scientific era (Carpo, 2017). Given this trend already in place, it is expected that the already explored use of digital tools in architecture will be strengthened in the future by AI systems and machine learning to the point of having complete designer-machine integration.

2.2.2 Fabrication-aware Design

The Second Digital Turn in architecture is a theoretical concept with a broad meaning, encompassing social, economic and cultural implications. These concepts have consequences on the profession of the designer, which consists in the technical and practical knowledge of the means of production of architecture. The ability to inform digital models so that they can "generate buildable formal solutions" is called fabrication-aware design (Pottmann, 2013). This design approach focuses on the production process so that it becomes an integral part of the design process, starting from the preliminary and ideational phase, helping to define the limits of the formal generation process and at the same time ensuring the constructability of the components. Algorithmic design represents the language that links formal generation to the mechanical programming of robots (instead of drawing a line "manually" we can set parameters using mathematical functions). It has already entered into contemporary architectural practice for the development of efficient and customized construction components. Examples include the Heatherwick Vessel in New York, the BIG's Isenberg School of Management and Business Innovation Hub, or the Zaha Hadid's Leeza Soho building in Beijing. The new relationship between the design and the built work and between conception and production was predicted by Branko Kolarevic in 2004. In the publication, *Architecture in the Digital Age: Design and Manufacturing*, he states that: "in the future, being an architect will also mean a builder, not literally, of course, but by digitally generating information to manufacture and construct buildings in ways that render present inefficient hierarchies of intermediation unnecessary" (Kolarevic, 2004).

The information process must start with the early stage phases of the project, in order to guarantee the success of the final assembly of the components. The flexibility of algorithmic models for the formulation of design parameters is effective for investigating the complexity that comes from the tectonic aggregation of technological units. Algorithmic models can be managed independently because of the data hierarchization. The structuring of similar data allows for the integration of the design process with data related to the geometry, to the physical, and mechanical characteristics of the materials. Dimensional limitations of tools become constraints for the manufacturing methods. This embedded knowledge allows for the expansion of design possibilities, without having to follow standardization processes, typical of off-site design. The fabrication-aware design process allows for the evaluation if it is more efficient to produce customized off-site components, to proceed with an on-site strategy, or prefab on-site. The speculative media around automation provides glimpses into future possibilities of on-site robotics construction with the ambition to shorten the production chain of components and to minimize transportation costs. It also allows integrating the two design streams:

- **downstream or top-down (form and program)**
- **upstream or bottom-up (component and fabrication)**.

Specifically, the downstream design process is informed by production methods, enriching the creative phase with data through the knowledge of tools that allow upstream cognitive integration. In this workflow, the algorithms are potentially the inputs for training technologies within the machine learning process. The architect uses technology to understand production. As a result, technical complexity can be handled to make better informed decisions and achieve better operations.

2.2.3 Digital transformation

The Fourth Industrial Revolution is primarily concerned with the production chain and is now laying a solid foundation for a broader-scale revolution, which involves business models, education, adoption of technologies (Fig. 2.2), and the organization of work. In a 2018 *Forbes*[12] article, Jason Bloomberg, clarified the meaning of the changes underway, focused on the difference between the concepts of digitization, digitalization, and digital transformation. Taking as reference the *Gartner's IT Glossary,*[13] digitization "is the process of changing from analog to digital form. The digitization process consists of transferring analogue work into the virtual world". In relation to the architecture profession, this means the introduction of the CAD tool, as a digital interface on which drafting shapes occur. Digitalization, instead, "is the use of digital technologies to change business models and provide new revenue and value-producing opportunities". This defines BIM as an operational tool that allows managing operational phases, budgets, and timing for the construction of buildings. The broader concept of digital transformation instead, "refers to the customer-driven strategic business transformation that requires cross-cutting organizational change as well as the implementation of digital technologies". It is an advanced digital ecosystem that can energize institutions and higher education through the use of digital products, tools, analytics, AI, and machine learning. In this scenario the operating methods lead to the inevitable and parallel development of technology, culture, and workforce[14] (Fig. 2.3). Using the words of John O'Brien, the Digital Transformation, or Dx is "cultural, workforce, and technological shift , and storage capacities".[15] What makes a transformation different from a change is the fact that it goes beyond tools impacting the culture of how we teach, enroll, and engage research. Moreover, Dx is "a commitment to the belief that the future will be an unapologetically digital future".[16]

12 "Digitization, Digitalization, and Digital Transformation: confuse them and you'll peril". Article by Jason Bloomberg in *Forbes*: https://www.forbes.com/sites/jasonbloomberg/2018/04/29/digitization-digitalization-and-digital-transformation-confuse-them-at-your-peril/.
13 "Digitization" in *Gartner's dictionary*: https://www.gartner.com/en/information-technology/glossary.
14 "A digital transformation isn't a single effort but rather a portfolio of initiatives that combine to scale the change. Having to "let a hundred flowers bloom" approach, where each initiative works independently in a spirit of experimentation, can yield interesting results, but it is not a formula for scaling a digital transformation across a business". From: https: // www .mckinsey.com / business-functions / organization / our-insights / nine-questions-to-help-you-get-your-digital-transformation-right.
15 "Digital Transformation, a caterpillar or a butterfly". Article by John O'Brien in *Educouse*: https://er.educause.edu/articles/2019/3/digital-transformation-a-caterpillar-or-a-butterfly.
16 "Digital Transformation, what is it?" Article by Ed Clark in *Educouse*: https://er.educause.edu/articles/2018/5/digital-transformation-what-is-it.

In the architectural profession the Digital Transformation redefines workflows, where the work phases happen simultaneously in contrast to the traditional sequential approach. Dx will inform decision-making at every level. Workflows in the Dx focus on analytics and data-driven decision-making. The skills required must refer to information technology and capacity to store and use data.[17] Consequently, the Dx will impact education,[18] and in particular on the higher ed,[19] that will drive the change. it is necessary to build skills and cultural support[20] to improve outcomes, especially in jobs that do not yet exist within a technological ubiquity and a dynamic economy where the new professionals will live.[21]

2.2.4 Connections between technology and Architectural Heritage

The evolution of industrial technology has changed the way of mass producing and therefore also the way of producing architecture. By focusing on Architectural Heritage, it is possible to examine how industrial revolutions in conservation have been affected.

The transition from the pre-industrial era to the First Industrial Revolution with the mechanical production powered by water and steam laid the foundations for the economics of scale that would irreversibly influence the culture of architectural design. The invention of the steam engine was also significant for the beginning of the Anthropocene geological era (Crutzen, 2006).

The Second Industrial Revolution marked a profound shift between the architectural languages of the early twentieth century and those of the past. The mass production of consumer goods also involved the manufacture of technological components for the construction industry. Economies of scale permitted entry into the market of economic and standardized building elements. At the same time, new materials were defined and the performance of existing materials improved. In this context the modernists laid the foundations for a new idea of architecture, rational, functional and uninterested in ornamentation. There was a growing awareness in giving aesthetic dignity to prefabricated materials that were the result of mass production. Examples of this are pivotal examples, after Joseph Paxton with the Crystal Palace, Le Corbusier's use of concrete, Mies Van Der Rohe with steel, and Louis Kahn with brick (the prefabricated historical material par excellence). A discontinuity emerged between

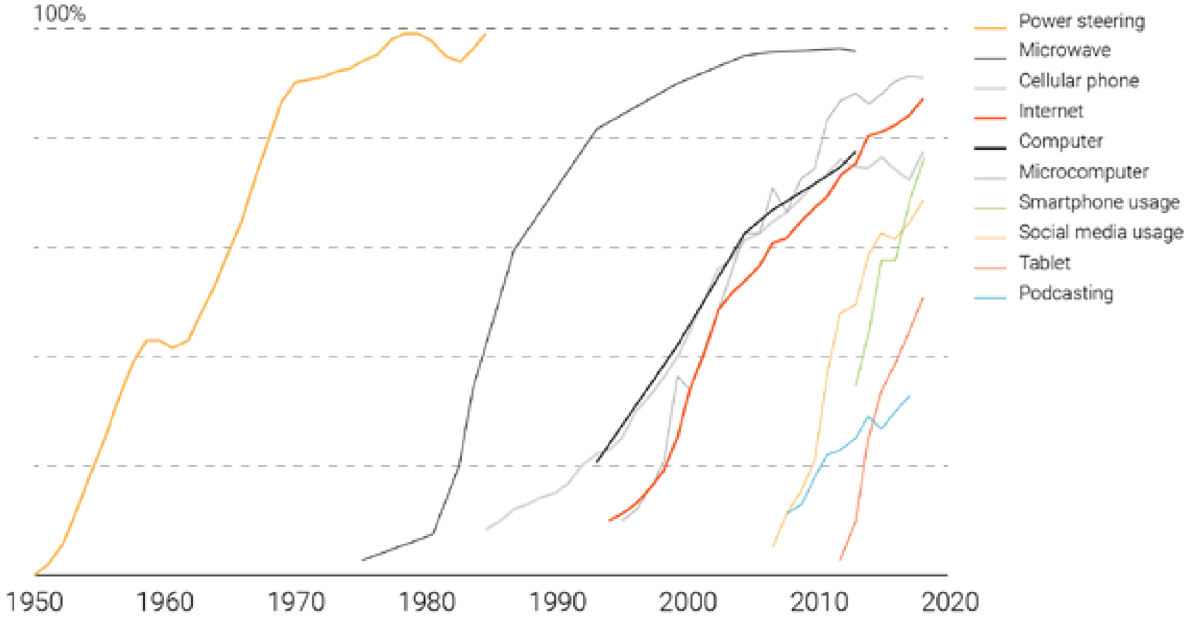
17 "Scenarios, Pathways, and the Future-Ready Workforce". Article by Jim Phelps in *Educouse*: https://er.educause.edu/articles/2018/8/scenarios-pathways-and-the-future-ready-workforce.

18 "Higher Education's 2019 Trend Watch & Top 10 Strategic Technologies". Article by D. Christopher Brooks and Mark McCormack in *Educouse*: https://library.educause.edu/resources/2019/1/higher-educations-2019-trend-watch-and-top-10-strategic-technologies.

19 "Changing Demographics and Digital Transformation". Article by Ted Mitchell in *Educouse*: https://er.educause.edu/articles/2019/3/changing-demographics-and-digital-transformation.

20 "The digital business transformation imperative" in *MIT Sloan Executive Education Blog*: https://executive.mit.edu/blog/the-digital-business-transformation-imperative.

21 "Digital Transformation Is Not About Technology". Article by Benham Tabrizi, Ed Lam, Kirk Girard, and Vernon Irvin in *Harvard Business Review*: https://hbr.org/2019/03/digital-transformation-is-not-about-technology.



" Digitization is the process of changing from analog to digital form.
Gartner's IT Glossary

CAD

" Digitalization is the process of moving to a digital business. It is the use of digital technologies to change a business model and provide new revenue.
Gartner's IT Glossary

BIM

" Digital transformation, refers to the customer - driven strategic business transformation that requires cross-cutting organizational change as well as the implementation of digital technologies.
Forbes (Jason Bloomberg)

WORKFLOWS

Fig. 2.2 Exponential curves of adoption of technologies. Source: https://www.visualcapitalist.com/rising-speed-technological-adoption/.

Fig. 2.3 Relationship between the advancement of digital technology and the tools for the production of digital design.

past aesthetic and constructive traditions with that of more contemporary approaches. The discipline of restoration had to confront this discontinuity through a growing repertoire of new formal choices that could be considered for interventions on existing buildings of value. The debate opened to new design approaches on existing buildings and this debate continues today.

The Third Industrial Revolution (Rifkin, 2014) exploited the power of information and internet data to optimize production processes and make these processes more flexible, pursuing the idea of mass customization (Davis, 1997). The drive towards high-tech and the qualitative component changed operational approaches toward that of architectural heritage. As Maria Luisa Germanà outlined in the paper "Technology and Architectural Heritage: Dynamic Connections" the culture of conservation in this socio-cultural context was expressed with the desire to define reliable operational methodologies for the recovery of damaged buildings, both from tangible and intangible perspectives. The first concept aims at a careful research of the most appropriate materials to be used in the restoration, so that they are compatible from the physical-chemical-structural point of view with historical buildings. The second concept refers to the need to structure the intervention phases in a systematic way, specifying the required skills, the necessary tools and the operating costs to carry out preservation, conservation, or recovery operations (Germanà, 2019).

The Fourth Industrial Revolution gives architects and conservation experts a "new palette of technologies that are evolving with unprecedented speed" (Schwab, 2017). In every specialized area of design, the architect has superpowers (Deutsch, 2019), which are amplified by: IoT technology, smart products, democratized automation, and cyber-physical systems. With reference to the field of existing interventions, architects express themselves through a digital language to reduce project uncertainties and ensure greater awareness in operational choices. Awareness is even more necessary for work on heritage, historically the result of a sedimentation of techniques acquired by craftspeople, which requires non-standard solutions to be defined on a case by case basis.

The emergence of production technologies (additive or subtractive) of material components capable of reading digital data and subsequently interpreting and reproducing its spatial characteristics (Gershenfeld, 2012), gives rise to new operational choices. These choices may concern the use of digital tools for surveying (laser scanners, cameras, sensors), diagnostics (cameras, endoscopes, ultrasound and infrared devices), or digital fabrication (3D printers and robotic arms). These tools are able to communicate with each other on-site and update the data collected on the current situation of a building in real-time.

On-site digital fabrication for restoration requires technical verification and feasibility studies (Willmann et al., 2013). However, it is expected that the interaction between technology and heritage may occur through the use of robots and drones programmed to carry out all the technical cognitive operations on the architecture being analyzed, especially in dangerous and inaccessible areas, for example following a structural collapse. The design language that will guide the customized construction methods of the Fourth Industrial Revolution is the algorithmic one, which is based on the overcoming of the concept of standardization.

2.3 Digitization of design processes: digital transfer and new culture of the project

Architects have always looked beyond the boundaries of their discipline, appropriating materials, methods, and processes from other industries as needed [Branko Kolarevic, 2003]

The first digital era in architecture began in the early 1990's resulting from the diffusion of software leveraging cheap processing power and the introduction of graphic interfaces (Bechthold, 2001). This period marked the transition from mechanical to digital technologies. The digital design software arrived from the industrial sectors for the production of boats, planes, and cars. In addition, animation software such as Softimage and Maya were developed for special effects in the entertainment industry. These sectors had been pioneering for decades, cars, airplanes and ships were entirely designed, developed, analyzed and tested in a digital environment, and were then manufactured using digitally-driven technologies. The research carried out was used to generate the drawings needed to automate the manufacture of the components. The concept file-to-factory was an appropriation from the aeronautical design industry - CAD file data to CNC manufacturing commands. It was taken to architectural design to control consistency and speed.

In the 1950's, the French car manufacturers Renault and Citroen carried out research to overcome the traditional form finding method for producing automobiles. The traditional process consisted of "producing a physical scale model and taking the measurements manually to then transfer the data necessary for the construction of the digital form to CAD" (Cross, 1977). The data necessary for the production and manufacture of components came from multiple, independent and uncoordinated designs. This process was replaced with the study of the mathematical relationships necessary to describe free-form continuous curves in space, carried out by the engineer Pierre Bezier and the mathematician Paul de Casteljau in the early 1960's. The calculation tools they proposed were configured as parametric notations or algorithms. These findings made calculus the basis for design and manufacturing, in an increasingly clear idea that architecture is a bigger assembly of units and components.[22] Through the parametric model it is possible to control the complexity of the flow of information that connects the virtual space to the real one defining the characteristics of the material, the parameters that describe the geometry, the constraints of the manufacturing process, and the assembly logics. An operational methodology allows the computational process to be used not only to automate processes but also to process large amounts of data. Citroen and Renault engineers in describing the calculus to generate the form of cars use the term "spline", historically derived from the lexicon of shipbuilding, "where it is described as a wood element that was bent and nailed to the timber frame of the hull" (Carpo, 2017). The methodology of creating full-scale prototypes for design, planning, and manufacturing also belonged to the aircraft production sector. Before the advent of

22 Greg Lynn, How Calculus Is Changing Architecture, TED talk 2009: https://www.youtube.com/watch?v=D-eyzUysMLy0.

digitization, planes were designed using full-scale drawings. Willow Run - Ford Plant,[23] to cite an example, was an automotive manufacturing complex in Michigan that during WW2 started building airplanes. Inside the plant, nurbs modeling was made manually. The typical curvilinear components (analogue version of nurbs) would later become common also in architecture.[24]

In the 1980's, Dessault Aviation SA invested in digital systems to reduce production costs. In 1981 the company developed and marketed CAD program called CATIA (acronym of computer-aided three-dimensional interactive application). CATIA's potential is from the ability to inform the production process, moving from a two-dimensional conception to an entirely three-dimensional one. Several tests and trials have followed the marketing of this software tool. One of the best known examples was the digital modeling and simulation process for the construction of the Boeing 777 "the first 100% digitally designed aircraft" (Kolarevic, 2004). In 1989 there was the realization of 500 Boeing models, they were "being assembled faster, more accurately, and less expensively than any previous airplane" (Abarbanel, 1997). To handle the amount of data needed in the design-production process, Boeing implemented CATIA with additional software, called FlyThru, to handle the magnitude of faster graphics needed to support the design process. The digital model is the result of a simulation process of dynamic phenomena, and consequent optimization, then subsequently used to extract the data and inform the manufacture of the components. The use of CAD / CAM systems has driven innovation in these sectors.

The production of ships (naval architecture is one of the oldest in construction) has always been to the attention of architects. Palladio drew inspiration for example for the construction of the roof of the Basilica of Piazza dei Signori in Vicenza, using skilled labor for shipbuilding. Last century, Buckminster Fuller used the typical aerospace methods to shape the Dymaxion car and house.[25] This relationship depends on the fact that both ships and buildings are complex systems: "interconnected spaces inhabited by people" (Kolarevic, 2004), with the difference that in addition to gravity ships must withstand hydrostatic pressure. As with aerospace engineers, shipbuilders no longer use drawings for the construction of these high-tech products with the utmost precision, but perform design processes with a "comprehensive three-dimensional digital model from design to production (Kolarevic, 2004).

CAD / CAM technologies represented a disruptive innovation for industrial production but its introduction into architecture arrived slightly later. With a broad perspective it can be argued that in the last 200 years only minor changes happened in construction. The industry is still putting things together in a similar way to what happened in the past. The building design and construction industry witnessed significant impact due to the advancement of CAD / CAM technologies. Unfortunately because of its reliance on highly specialized labor, the recovery field has yet to be affected by these technological advances. Digital fabrication would be useful as a way to materialize digital objects, bridging the gap between digital and material. This gap is a place for exploration: "designing straight from the designer's software to complementary software controlling the object or component of the software" (Sheil, 2012).

The transfer of algorithmic-parametric design technologies like CATIA in architecture is due to the work of Frank Gehry. The Fish sculpture created in 1992 in Barcelona was the first object on the architectural scale to be represented with paperless methodology without two-dimensional paper drawings. Gehry used CATIA to quickly manage the physical transposition of complex and sophisticated components. The Fish sculpture was feasible thanks to the support of the shipbuilding industry. The same also happened for the Guggenheim Museum in Bilbao. As a result, Gehry is the promoter of the entry of digital fabrication in architecture (3D Building Model) and of the file-to-factory strategy, which characterized the Digital Turn. Through this methodology, professionals can send directly the project to the fabricators. In doing so, responsibility balances and work relationships inevitably change.

Through digital fabrication it is possible to materialize the complexity of virtual spaces or components, guarantee diversification, and break down the barriers of creativity determined by the limits of traditional representation and manufacturing tools. The first approach to the discipline outlines a series of manufacturing strategies in relation to formal generation techniques in which the architectural idea and the characteristics of the material are integrated from the initial phase of the design process. The introduction of innovative digital manufacturing technologies, such as the use of industrial robots and the definitive affirmation of 3D printing, has reduced the gap, in physical and procedural terms, between designer and manufacturing process, favoring the rediscovery of architecture as material practice (Figliola, 2017). The availability of these tools has facilitated the exploration of file-to-factory strategies. Laser cutters became mainstream tools. 3D prints became quite normal. Recent experiments on the subject involve the construction of digital models through which the architectural idea and manufacturing are conceived as part of the same workflow.

Three-dimensional digital modeling opened up formal possibilities for creative exploration in architecture. The use of digital parametric and algorithmic design has facilitated the transition to a new digital style. New forms are created by generative processes in novel ways within reasonable budgets. However the use of curving, isomorphic surfaces, and smooth curves is not only due to the spread of digital design tools. There was already a desire in the current cultural "debate to overcome post-modern language and deconstructivist fragmentation" (Carpo, 2013). The opportunity to push architectural design towards a new cultural paradigm by exploiting the Digital Turn is created and produced using a process that allows professionals in the supply chain to interface with a common language from design to production through: design - analysis - representation - fabrication - assembly. This system is also called Digital Continuum (Leach, 2002). The representation and manufacturing

23 Willow Run - Ford Plant: https://www.thehenryford.org/collections-and-research/digital-collections/expert-sets/101765/.

24 From the kick-off lecture of CritPrax class at Lawrence Technological University by Karl Daubmann.

25 Antoine Picon in Made by Robots: "according to Fuller, the Dymaxion house that he developed in the 1920's and 1930's were not only devices meant to revolutionize the building industry, transportation and everyday life; they were a way to make a radically different future in which men would roam free on the surface of the globe, and take their intellectual capacities".

implications of the digital continuum have been made explicit, for example, with projects such as the cover for the London Waterloo station built by Grimshaw in 1993, and the London City Hall created by Foster and Partners in 2002. In both cases, the architects did not draw the final form but used programming languages through which the morphology was generated, and consequently, the three-dimensional model used for its transposition into physical space (Burry and Murray, 1997). In particular, the International terminal at London's Waterloo Station laid the groundwork for Grimshaw's use of associative geometric system. The project was conducted by performance-driven design through an examination of material properties and structural forces with finite elements analysis. The geometry for the parametric roof model is complex without being complicated. It embeds the intelligence of fabrication methods and material properties into an algorithmic design model where changes could be made dynamically on-the-fly; algorithms handed to the contractor for fabrication and assembly (Burger, 2012).

In summary:
1) the spread of CAD systems displaced design drafting;
2) the spread of parametric tools made it possible to manage the processes entirely digitally;
3) the Fourth Industrial Revolution, ubiquity, and interconnection between the production tools will involve an update of the digital workflows within the Digital Continuum. These are the issues with which this dissertation research pays particular close attention.

2.3.1 Digitization in restoration, from BIM to HBIM

The emergence of BIM technologies offers the possibility of creating optimized information models, ie transparent digital documents containing all the information regarding the entire life cycle of the architectural work. In this type of process, the informative character of the model becomes predominant over the geometry. The value of BIM resides in the generation of the form through parameters and in the definition of the technical-managerial aspects (Dore et al., 2015). The idea of a digital model of the built environment can be considered a representation, simulation, or software output. The representative tools for the management of the project are today characterized by a constant evolution from the basic nature of the design to the sophistication of the model, from which to extrapolate the production drawings of architectural elements (Fig. 2.4). The BIM concept originates prior to 2D drafting of the 1980's. BIM is based on the idea of creating a single 3D building model with drawings extracted from the model considered as derived data (Aish, 2013). But drawings only need to be extracted if required by contractors or building officials and this process may soon become extinct.

A new process is described as HBIM (Heritage Building Information Modeling), a term used for the first time in 2009 in a scientific article by Maurice Murphy, and his colleagues, of the Dublin Institute of Technology (Murphy et al., 2009). In this scenario, a mapping of BIM objects occurs on a 3D surface model. This final stage process creates a navigatable model with deep metadata and material makeup. HBIM focuses on what information is required in order to achieve efficient conservation strategies starting from representation (Germanà, 2019). The main requirement in the use of BIM

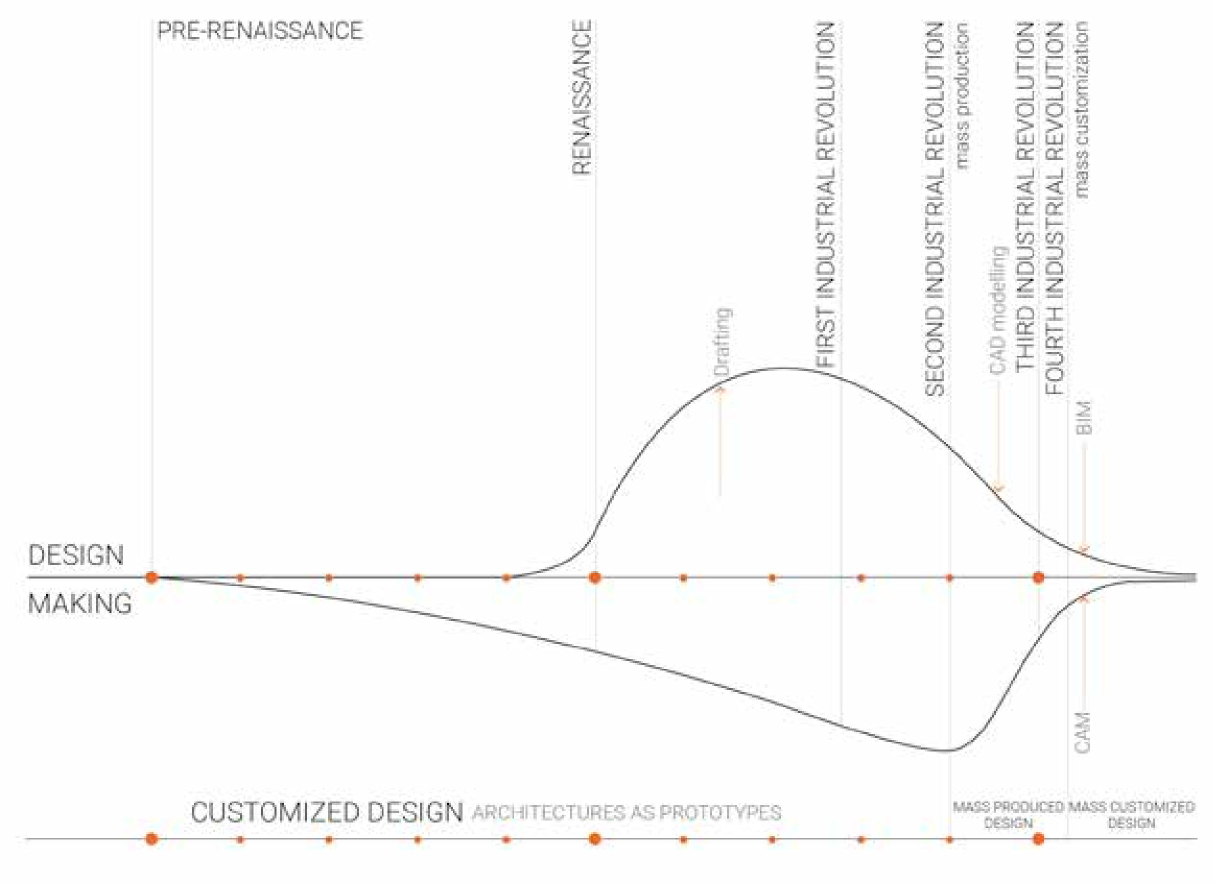


Fig. 2.4 Contraction and deviation in design and making through industrial revolutions.

for the representation of historical architecture is the quality of the model and its reliability regarding geometry. A second condition involves the addition of a complete database of historical notes relating to each component on materials and changes over time. Semantic organization is central to BIM software. In the near future, the collection of data of all significant aspects in a 3D content will allow HBIM to become the best way to manage the process from investigation to restoration (Quattrini et al., 2015).

In addition to HBIM's systems, it is expected that it will soon be possible to connect on-site digital tools, defining context-aware systems with applications in the domain of Cultural Heritage. The use of sensors will allow for predictive models that will allow data-based decisions to be made. In The Age of Intelligence, the autonomous communication between intelligent devices will allow for the development of context-aware computing. "Cultural Heritage is a domain where the widespread diffusion of ICT technology and sensors can strongly enhance the quality of the offered services and subsequently create a Smart Cultural Environment" (Piccialli and Chianese, 2017).

2.4 The democratization of robot scripting with generative algorithmic design

"The same rules that generate new spaces and new geometries are translated into information to govern numerical control machines that produce these shapes [Emilio Pizzi, 2013]

The division present during the First Digital Turn between design and architectural production was overcome by the democratization of the machines, the result of the Third Industrial Revolution, and to the simplification of the methods of communication between the digital model and the manufacturing tools. Communication between the geometric CAD model and numerical control machines was made possible through the conversion of source files, generating a design-to-production or file-to-factory process.

The CAD-CAM processes are simpler and faster as a result of the direct relationship with digital fabrication tools able to share the same space as the designer. If robots were outfitted with sensors capable of processing and interpreting incoming information then they became an extension of the work space in the physical world as well as a cognitive extension. In this working context, production becomes the designer's competence. The manufacturing phases can be managed in the same digital environment in which the project's form is generated. This allows the architect to explore the design possibilities by developing customized processes that maintain the same efficiency as serial production.

Today it is possible to generate the code necessary to drive the production machines. One of the programming languages through which to define the geometry and manage the movements of the robots is defined by the Grasshopper plug-in Kuka | Prc™ (Fig. 2.5), released in 2011. It works in the three-dimensional modeling software Rhinoceros. The programmer of Kuka | Prc is Johannes

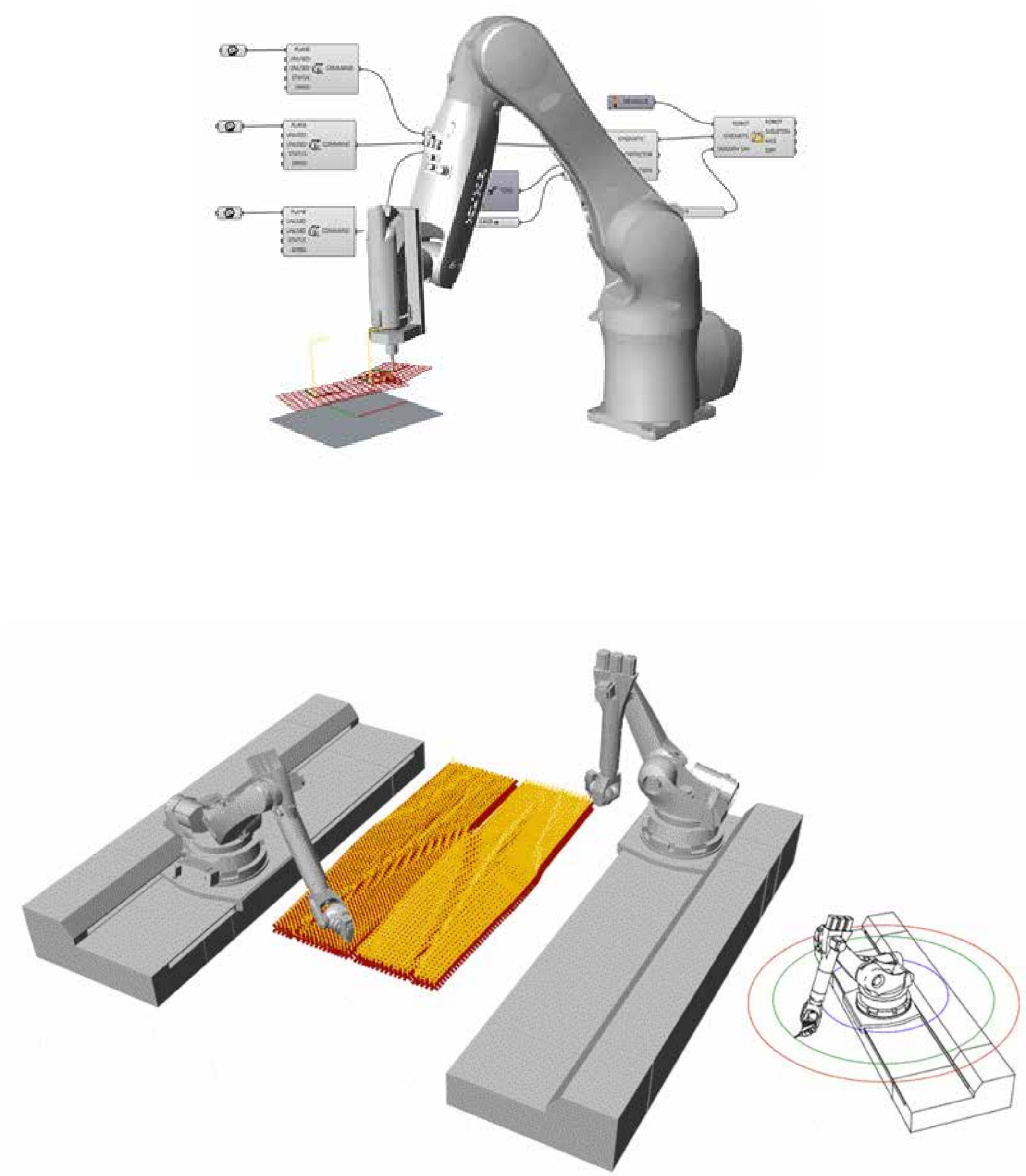


Fig. 2.5 The interface of Kuka|Prc, a Grasshopper plug-in for robotics programming in an algorithmic design environment. Source: https://forum.robotsinarchitecture.org/.

Braumann, founder, along with Sigrid Brell-Cokcan of the Association for Robots in Architecture.[26] Through Kuka | Prc, robotic programming takes place within an architectural software through parametric generative modeling (Mitchell, 1998). It occurs through the construction of mathematical models, or algorithms, which become the mediators between digital and physical spaces. In turn, once the informative model is defined, the robots become mediators between project and realization.

Algorithmic design goes beyond parametric design by opening unexplored scenarios for the management of architectural form. From informational data as computable design, architects move onto the elaboration of variables that drive the project to become matter through an integrated and controlled digital environment. Luigi Moretti (Mulazzani and Bucci, 2002) and the works of Sergio Musmeci (Nicoletti, 1999) are precursors with this working method (from a pre-digital era) that focuses on the definition of the algorithm rule. Algorithms are not only describing the geometric and mathematical relations of a form, but additional, possible variations. The elaboration of free-form shapes can be implemented as a result of this process of exploring new languages, in mimesis with natural processes. Robotic algorithms allow designers to manage the multiple parameters necessary to calculate the movement of the six axes that describe the kinematics of industrial robots. The movements are programmed by defining a sequence of planes in space, each with a specific orientation with respect to the design geometry, tool, and end-effector installed on the robot. The geometries of the design outcomes are then broken down into toolpaths which can be traced back to basic elements such as target planes, positioned on continuous curves in three-dimensional space (Fig. 2.6). Unlike direct modeling for design exploration where each geometric object is based on explicit coordinates, the toolpath programming adopts algorithmic modeling, more suitable for complex systems. It will help the designer to set up relationships and restrictions from which the design will result.

Each manufacturing method, additive, subtractive, or composite involves the use of a sequence of operations that describe:

- the robot model used, based on a preset catalogs accessible within Grasshopper, of robots, tools and controllers ready-made to populate the scripts
- end-effector installed (spindle, nozzle, hot wire cutter etc) to exploit the flexibility of the robot
- any external axes supporting the manufacturing process (linear axes or rotating tables)
- accurate real-time simulation of the kinematics and collisions, necessary to validate the programming code before using it in the physical space,
- sequence of movement and therefore of production
- production parameters such as speed or pauses
- trajectory diagnosis including detection of out-of reach and singular positions (movement limits)
- the script to export and insert in the robot to execute the process.

Kuka | Prc is an intuitive interface that allows designers to focus on the process rather than on the technical aspects. The software plug-in is divided into the commands: robot, toolpath, tools (customizable), utilities, and cores. Once defined, the type of robot and the end-effector (among

26 Robots in Architecture: https://www.robotsinarchitecture.org/about-robarch.

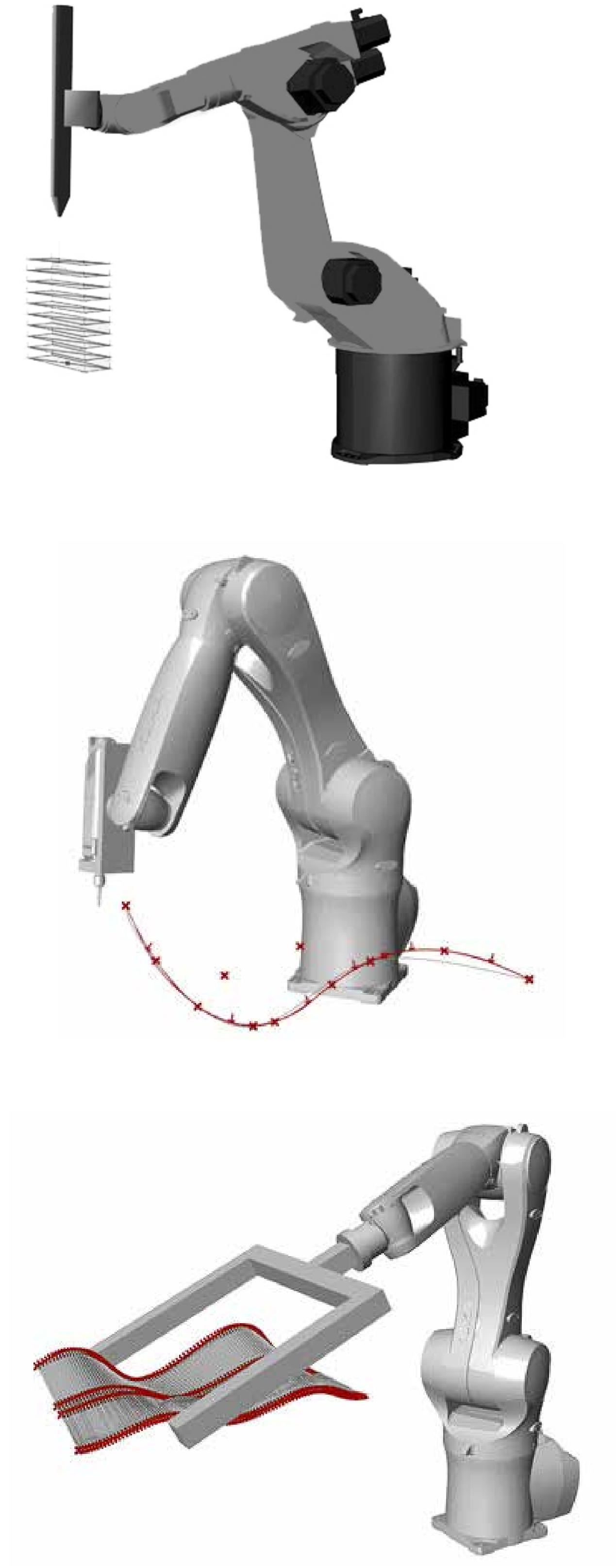


Fig. 2.6 Algorithmic design functionality to program robots to perform different tasks using various end effectors. 3D preview visualization allows for correcting kinematics errors in advance, before completing operational sequences in the physical world.

those pre-purchased or with DIY geometry) it is possible to associate the trajectories of movement to the types linear, point-to-point, circular, or spline. Finally, through the Core the planned manufacturing sequence is transferred to the robot. The code extracted, deriving from algorithmic scripting, is in .src format. Before exporting this file, designers can view an animated simulation, which allows them to diminish unpredictability.

As part of this research, Kuka | Prc was used to manage a process of robotic additive manufacturing (RAM). The AM provides for the definition of numerous parameters. The expected volumetric result must be broken down into parallel lines at a constant distance (contours) which represent the extrusion layers. Each layer is then decomposed into target points by an arbitrary density that the end-effector's nozzle must reach to deposit material. Each target point is defined by an xyz coordinate system, which defines the direction in which the nozzle must approach the targets. The inclination of the target vector allows orientation for the extruder in the space. In addition to designing the extrusion path, a designer can define the thickness of the layers. The material deposition speed from the tank to the nozzle must be synchronized with the robot movement speed. This also depends on the diameter chosen for the nozzle. All the parameters used to manage the path of the extruder-nozzle-target material also depend on the properties of the material and its variability. The management of these aspects in the decision-making phase is comparable to the technical choices that are made by artisans skilled in architectural conservation. In this case, manual production translates into the production of variables through a new material sensitivity (Figliola, 2017). What makes the robotic design democratic is not only the accessibility of the interface, but also the community supporting it. Johannes Braumann has defined a knowledge exchange point that is configured as an online forum[27] where a designer can share projects and share problems that require troubleshooting with the community. This direct relationship with the professionals who interface in the world of robotics also makes it possible to create a solid network in the academy, in the industry, and in the Fablabs. In this way the educational path continues independently even outside the channels of higher education. Through this design methodology it is possible to disseminate a common language between architects and designers, based on the definition of design parameters.

2.5 Tessellation: a workshop to explore parametrically driven design and assembly

"You never change things by fighting the existing reality. To change something, build a new model that makes the existing model obsolete [Richard Buckminster Fuller, 1982]

Several moments of comparison occurred between this research and with the research carried out at Lawrence Technological University of Southfield (MI - USA) and Polis University of Tirana (Albania). During the third year of this research a point of contact was defined with the doctoral research of James Stevens and Gerdi Papa. This overlap represented an opportunity to combine knowledge and skills in a shared project where all three research endeavors explore digital fabrication in architecture. It was decided to exploit this collaboration to organize a two-week workshop called Tessellation at U-Polis. The workshop investigated the constructive principle of tessellation to create a large-scale prototype supported by algorithmic design and additive manufacturing. An earlier experiment case that shared the collective ambition of the Tessellation workshop was the Parametric Spatial Structure. The preceding workshop resulted in a bamboo prototype at the School of Architecture of the University of Minho - EAUM. For this project the working group focused on formal research and structural optimization given the fragility of the bamboo material. In this case, the construction logic required rationalization through standardizing the size of the linear elements on the basis of an average size within which the bamboo stem is not interrupted by a knot. This prototype required an internal support structure as formwork during its construction. The connections between the basic linear units used plastic zip ties.

Tessellation is a technique widely used in the history of modern architecture (Fig. 2.7) and with a contemporary resurgence due to digital computation (Fuller, 2001). Geometrically, tessellation is the process of dividing a plane using one or more geometric shapes without overlapping and without gaps (Fuller, 1982). The constructive strategy of tessellation allows complex volumes to be realized through the assembly of simple components (Papanek and Fuller, 1972). Choosing tessellation techniques brings the geometry back to relatively simple mathematical relationships. These relationships can then be expressed through a digital generative algorithm with subsequent guidelines for form-finding and a predictive tool for the manufacturing phases.

The Tessellation workshop introduced the geometric concepts to the students, allowing them to explore a range of forms. Given the short time for the workshop, material constraints defined the use of a simple and available low-cost material of flexible PVC electrical conduit. The PVC elements were 3m in length and a diameter of 20mm. In contrast to the simple linear PVC elements, the joints contained the intelligence of the geometry and assembly.

The tools of the FABRICA Lab (U-Polis) created the connection joints using rapid additive prototyping. Additive manufacturing produced the custom connection joints to facilitate manual assembly of the components. Particular attention was paid to the assembly sequences, especially in the intersections between vertical and horizontal linear elements. One ambition was to carrying out the assembly without resorting to external support structures as an advancement of the work from the preceding Parametric Spatial Structure prototype.

The concept of smart joint was also explored in the context of the mass-customized open source design. The XT-CF20 bike, promoted by the colorFabb hub, is defined by a frame composed of metal bars connected by 3D printed plastic joints. The joints can be customized with the aim of optimizing performance and ergonomics, together with the constituent elements of the frame which can be in carbon, titanium, aluminum or bamboo. In turn, demonstrating the fact that almost all complex artifacts require joints in the naval, aeronautical, and architecture industries (Kieran and Timberlake, 2004). The intelligence of the joints lies at the same time in the possibility of separating different materials or joining materials that cannot be manufactured or transported in the dimensions required

27 Forum of Robots in Architecture community: https://forum.robotsinarchitecture.org/.

by the project. For the Tessellation workshop, the formal volume of the 1:1 scale prototype (Fig. 2.10) was modeled through generative algorithms entirely in Grasshopper. Three different diameters offset vertically defined the prototype. Through subdivision of the curves and management of the mathematical domain, linear units defined connection at predetermined points in space according to a lattice scheme. The 4m prototype took into account the material properties, material curvature, and the fragility of the intersecting nodes. Moreover, with this methodological approach, the nodes did not represent an imposed initial condition, but an active element where design was carried out in parallel with the formal manipulation of the overall outcome. Various design iterations hypothesized the intersecting nodes between the PVC elements. In particular, this optimization process ensured that the timing of 3D printing was compatible with the time window imposed by the duration of the workshop.

The algorithm that defines the joints was able to adapt to different geometrical configurations and produced varied design iterations. These configurations used different angles of curvature with respect to a horizontal plane (Fig. 2.8). Comparison of the overall volume and the construction lines provided verification for procedural correctness. To further analyze the joints, it was necessary to develop the surface of the prototype, so as to transpose the three-dimensional elements into lines projected to the surface. Knowledge of the material was used to optimize the Grasshopper script through Galapagos which is a genetic algorithm component (Tedeschi, 2014). This allowed for the approximation of joints to a single three-dimensional model with similar inclination angles.

Grasshopper's working environment offers the possibility of using the Galapagos genetic solver able to find the minimum or maximum of a given function. Therefore, once the design parameters are precisely understood, it is possible to define dimensional, geometric, or kinematic limits within which the final output is confined. Starting from what is called the initial population of algorithmically processed elements, the objective function is defined with a new genetic attribution that is associated with each element of the population (Mitchell, 1998). The solver at this point recalculates the formal outputs based on the new limits imposed by the function from which a new generation of elements is derived. In the case of the workshop, once the angle of inclination of the vertical rods was calculated through the development of the geometry on the plane, the minimums and maximum inclinations of the joints was set. Once the criteria was set the output approximated the elements with angles of deviation less than 10 degrees. This approximation was assessed as possible because the flexibility of the plastic linear elements was taken into account.

For many of the student participants, this was their initial foray into the use of Grasshopper as a design tool. As a result of this digital design introduction, the choice of a simple material helped to manage the complexity and expectations. Before approaching the large-scale prototype, it was appropriate to carry out short exercises so that the students could become familiar with the constructive logic of the tessellation. These short exercises were made with small-scale plastic models. A critical design approach is necessary when using algorithmic form generation because the software simulates the geometries real-time in digital space. In the process described above, it is unnecessary for designers to trace each technological unit as they are produced based on the logic of the algorithm. Given the

Fig. 2.7 Above: Fly's Eye Dome", a structure designed as a cheap dwelling in 1965 by Buckminster Fuller. It is a double-skin truncated sphere fifteen meters in diameter. The dome was based on Buckminster Fuller's mathematical research and on the principle of enclosing the largest volume of interior space using the smallest surface area, a sphere. This structure could offer immediate shelter to people in urgent need. The openings embedded in the dome as windows, doors, vents or solar energy cells. Below: US Marine Corps transporting a 55ft dome designed by Buckminster Fuller via helicopter, 1954.

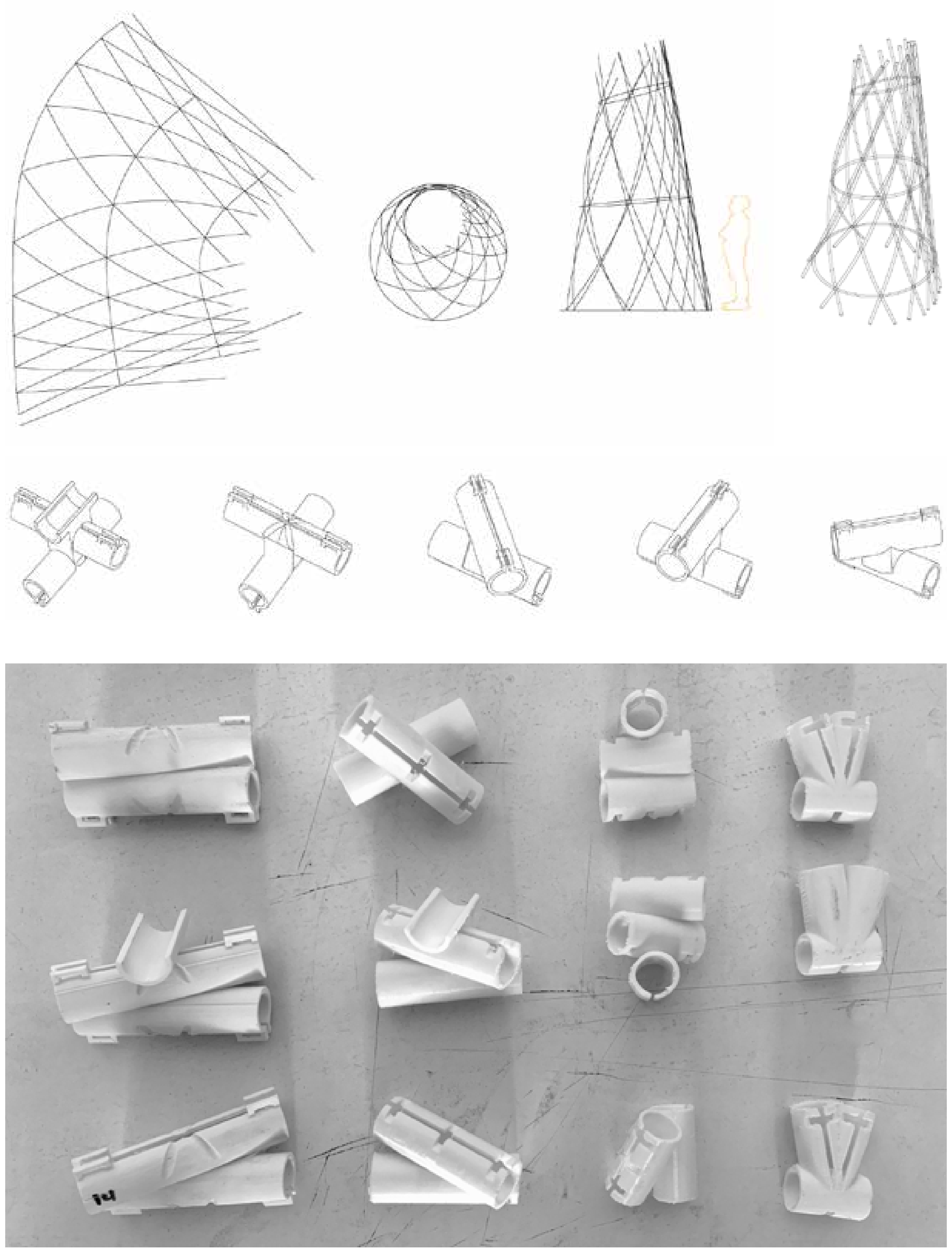


Fig. 2.8 Above: Digital model of the built prototype. To define the angle of inclination of the construction joints, the surface was unrolled on a flat plane. Once the joints were inserted and directed on the XY cartesian plane, a check was made so that the rotations were geometrically verified in three-dimensional space.Below: Design iterations of the construction joints. Through the various iterations the geometry was optimized to reduce the additive manufacturing time and to ensure adequate structural performance. The parameters that guided the design were internal diameter, external diameter, overall length, angle of inclination and density of 3D printing.

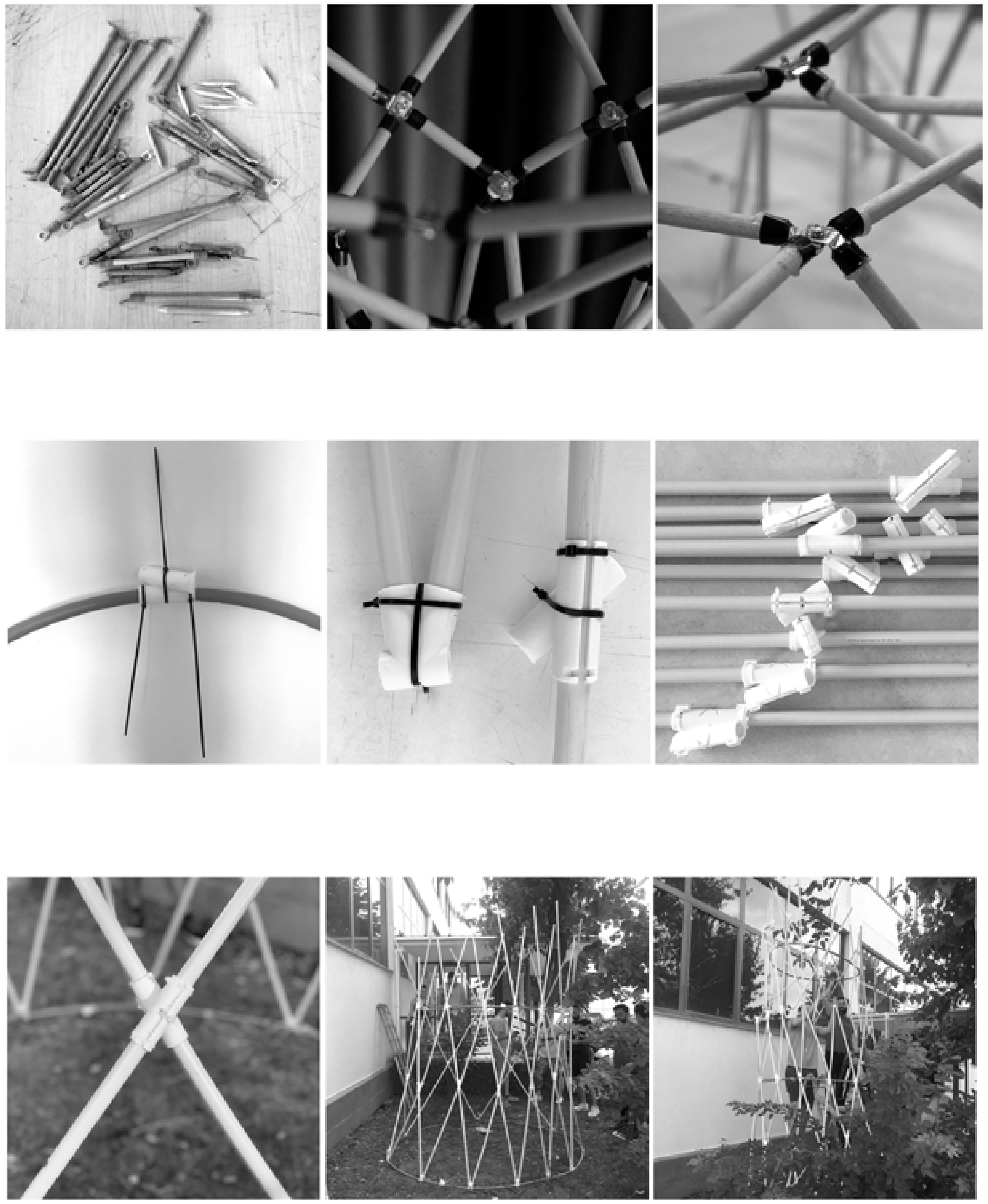


Fig. 2.9 Above: student study models verifying the principle of tessellation at a small scale. The students also provided technical drawings as a guide for the realization of the three-dimensional geometry and assembly diagrams of the technological units. Central: preparation of the construction activity for the prototype at 1:1 scale. Below: implementation phases of the prototypes and implementation of the material.

potential of Grasshopper capabilities, the workshop students were able to automatically extrapolate the lengths of each connection segment between the joints. On the basis of all design and simulation information, the construction phases were updated intelligently throughout the process (Fig. 2.9). The 3D printed joints were numbered and inserted at the correct distance, following the indications deduced from the software simulation. This element-joint association followed the digital prediction and optimization process.

Once the construction units were set up, the workshop participants proceeded with the assembly of the prototype. The a priori work served to facilitate and speed up the implementation phases, which took only 3 hours. The speed of execution was a relevant topic also for the construction of the prototype structure, which was conceived as a low-cost structure to be used in emergency conditions. In a scenario of this type, for example, one can imagine preparing 3D printing of construction joints and using them as the sole guiding element for the erection of a low-cost temporary structure. The joints themselves were the distinguishing element of the Tessellation Workshop, for two main reasons. Firstly, the joints were performative for construction as the angles of directionality and the numbering of the joints themselves did not require the preparation of any technical drawing that contained assembly instructions. Secondly, the solidity of these technological elements together with the flexibility of plastic conduit meant that there was no need for any internal temporary support structure. In contrast, the students from the previous bamboo case study had to define an algorithm to predict the positioning of the nodes. With the nodes defined at the most rigid sections of the bamboo elements the ideal length of the individual segments needed to be defined where to cut and where to join with the zip ties. The decision to use an artificial synthetic material accelerated the preliminary study phases of the project. The simple linear elements provided consistent dimensionality and structural homogeneity over the entire length resulting in no need for the involvement of algorithmic transcription of elements like that required in the bamboo workshop.

The construction of the large-scale prototype was an opportunity to convey to students through a practical exercise, some topics on which the international scientific community is currently confronting. The process involved the simultaneous design of the form and construction details. This simultaneity highlights the differences with the traditional methodologies for which the design sequence is more rigid and there is a clear distinction between volumetric definition, choice of materials, and definition of details. We did not want to maintain a hierarchical approach but integrated the elaboration of the joints within the process, bearing in mind that current experiments have highlighted how "the least desirable place to join materials is the point of final assembly, at the far end of the material supply chain" (Kieran and Timberlake, 2004). The material choice as input was the generating element of the form, combining the digital process with analog material experimentation. As part of this educational activity, the workshop extrapolated the principles of the so-called Second Digital Turn (Carpo, 2017).

The generative logic of the form was managed in parallel with a process of optimization and definition of the data necessary for digital fabrication. The workshop tightly controlled the process in order to materialize the digital space while simultaneously predicting and resolving the complexities before the final realization, demonstrating the design potential over earlier two-dimensional era methodologies.

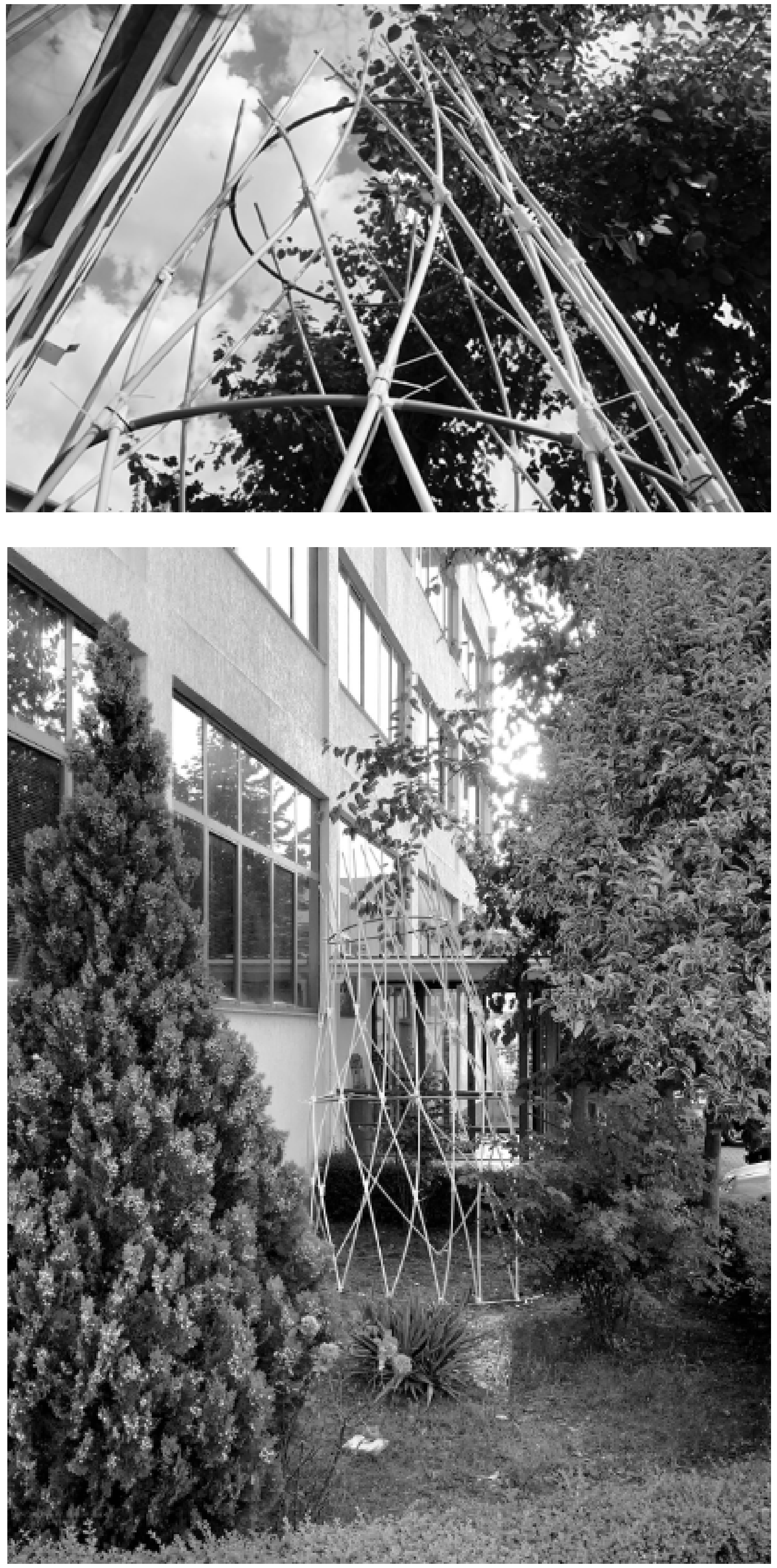


Fig. 2.10 Full-scale parametrically designed prototype made during the Tassellation workshop, installed at Polis University in Tirana.

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PART II - STATE OF THE ART IN ROBOTICS

3 The industrialization of building products

ABSTRACT

This chapter investigates the relationship between the construction process and historical attempts to innovate workflows for the installation and assembly of construction components. Taking a broad view on industrialization, prior to 1797 everything made was custom in many ways. Construction is in the business of customization. Every building site is unique. Every building has some level of uniqueness. Given how unique buildings are, the industry is set up in an individualistic basis. Every building built is a one-off prototype. Our industry suffers because it is very common for buildings to be over budget and behind schedule, and these are two things that mass production has been able to deliver. Architects have long complained about the quality that results from the construction industry and now because of digital design one could imagine that architects can pre-simulate the construction process. Architects might be in a great position to introduce increasing levels of automation including robots into the process.

The race for automation on the construction site happened between the 1960's and the 1980's in countries like USA and Japan that invested in the most technological advancement towards automated housing prefabrication, on-site single task construction robots, and integrated automated construction sites. The lack of skilled labor in the building industry was a driving factor to lead the promotion of automation in prefabrication and construction. It was an alternative to traditional construction practices. The enhancing of research in this field during the following decade was based on the 'robot boom' in the manufacturing industry. As a consequence, the adoption of robots was a logical -experimental- approach. Single task construction robots were subsequently developed. They could be used on construction sites for demolition, surveying, excavation, paving, tunneling, concrete transportation and distribution, concrete slab casting and finishing, welding and positioning of structural steel members, fire-resistance and paint spraying, inspection, and maintenance. Sites would be structured and designed like factories. The final objective was the implementation of automated manufacturing and construction technologies. One of the reasons why the past efforts of automating constructions didn't have a continuation was because computing power was still weak. Moreover, robotic applications required high initial installation costs. Technology has evolved substantially since the 1970's-1980's. The cost of robots is dropping worldwide. Today, a perfect storm is finally enabling the construction industry to take ownership of innovations and be the avant-garde of future change.

Keywords: *Construction Process, Architectural Production, Mass Customization, Building Automation*

3.1 A conversation about mass customized architecture

During my time as a visiting scholar at LTU, I had the opportunity to teach the *Introduction to Robotic Fabrication* course with Karl Daubmann. In this context, we presented both case-studies and speculative roles of robots (and technology) in the construction industry. In addition, students were exposed to Karl's work in manufacturing at BLU Homes where he worked with a large multidisciplinary team to design prefabricated, customized homes.

This work occurred across the US and operates here to give insights to a broader discussion of mass customization and future trends in the construction industry. His experience is unique in that he straddles between design, industry, and academia and I wanted to engage him on these topics through an interview format to incorporate his tacit understanding of the industry. Karl is also the Dean of the College of Architecture and Design at Lawrence Technological University where he is bringing his experience from industry to academia so that students will be exposed to these tools and approaches as a means of being ready for the changes coming with the Fourth Industrial Revolution.

Sara: *Thanks for taking the time to discuss these topics as a means of sharing your experience and framing aspects as they relate to the topics of my dissertation. To start, can you give me a bit of background on your work in industrialization and manufacturing.*

Karl: As you are aware from the course, I enjoy sharing these stories and experiences from practice. Practice or industry doesn't always map well onto academic contexts. My interests in design, technology, and manufacturing began with my teaching, academic research, and design practice (PLY Architecture from 2000 - 2012). I had the opportunity to teach in these areas at the University of Michigan and our practice did a number of restaurant interiors where we designed and built a series of intense / custom projects. Given CAD/CAM technology, we were able to build these in quick and inexpensive ways because we leveraged the intelligence of our digital design models. In 2010, we were approach by BLU Homes to work as their creative direction team. This was an opportunity to develop houses as products and to be part of an integrated team and work at a broad scale. From 2012 - 2014 after leaving my practice, I assumed the role of Vice President for Design and in this capacity dealt with product development, design, and collaboration with sales, marketing, engineering, and manufacturing. It was in this role that I began to understand much broader issues of complex, impactful problems and how design might have greater agency in these bigger problems.

Sara: *You mention being part of an integrated team at BLU Homes. One topic that I explore in my dissertation is this notion of the master-builder and the way that I imagine industry, education, and professional practice to have to evolve to meet an increasingly complex world of construction. Especially related to Cultural Heritage, I expect changes in labor to have consequences on the design teams and on the make-up of the on-site teams. What is your sense of this potential for the master-builder and have you witnessed this in the construction industry?*

Karl: I've thought about this topic of master-builder quite a bit and I think it emerges from my own experience where I grew up in a small fabrication shop and was exposed to construction and technology long before I attended architecture school. This experience at a young age informed the way I understood materials, innovation, and economics. In my own practice, I explored the potential of the master-builder in two different ways, first as a boutique design / build practice, and second within an integrated team of design and manufacture. At PLY we leverage our digital design and knowledge of digital fabrication to handle all aspects of commercial interiors. We had control over materials, means and methods of construction, and understood firsthand how it impacted the budget. When we began we were less confident about what we were doing because it was a non-standard form of practice but as we advanced we began to understand the contract, roles, and economics in much more sophisticated ways. In the US, architects are kept away from the cost as this role is owned by the contractor, which in turn gives them much more agency and risk in the process.

One thing that worries me about the trajectory of practice in the US is the move to specialization. While specialization protects clients by giving the designer specialized experience in specific building types, I see a lack of innovation occurring in these areas. And while some projects may not require creativity, I fear that the rush to respond to liability risk may also eliminate innovation. This relates to the master-builder because I imagine the master-builder as being able to innovate with an understanding of both convention and innovation while responsibly managing costs.

Designers in this type of role will give themselves incredible agency in the process. Obviously there is a relationship between risk and reward. I was speaking with Tom Leslie a few years ago and he explained to me that all of Nervi's projects were competitively bid, meaning that they were cost-effective proposals. This blew my mind because we know Nervi's work as being beautiful and expressive, not as the most cost effective way to build. Nervi is a great role model as the master-builder. Today the opportunity is to leverage the interconnected relationship between design and construction, means and methods to produce innovative design and construction. I don't think the master-builder will be a singular person working in isolation but instead be part of a collaborative and tightly-integrated team. To successfully work in this manner I believe it will also require changes to the way we educate young designers and builders.

I've always believed that our contracts, roles, and responsibilities define our professional actions. With BLU Homes I was excited by the integrated model where the disciplines were all on one team (same company). From the master-builder perspective, the design team played an important role as integrator. As product design we worked with and supported the strategic team and the marketing team. As project designers we supported sales because we knew the products, codes, and constraints, and we fed accurate information to the engineering and manufacturing teams for the construction and permitting of the houses. We had designers, architects, programmers, BIM experts, technologists, and even a librarian on the design team. While I don't view any one individual as a master-builder, the design team played a role like the one you suggest. In addition to your focus as the master-builder as engaged in downstream construction activities, at BLU the design team had as much effort upstream with aspects of sales, marketing, and client-facing aspects. In this way I would argue that the master-builder might be able to engage greater and greater amounts of data and be more inclusive of a wide-array of potential design inputs.

Sara: *I want to pick up on your point about scaling things up. I am looking at the potential for robotics to be more widely deployed on cultural heritage sites and we will get into that specific issue soon. But before we do, I want to make sure I have an understanding of industrialization and the mass-production landscape.*

Karl: If I take a very broad view of industrialization, I am always amazed at the deeply held beliefs that reside in design and construction as it related to mass-production. I began practicing in the late 1990's when we were all talking about mass-customization. As a frame of reference, we all assume mass-production as a given but prior to 1797 everything made was custom. Eli Whitney's patent for interchangeable parts on rifles initiates industrialization in the US but the proof of concept for the patent was three rifles made by hand to a high tolerance so the parts could be interchanged only on those three guns. It is important for me to make this clear to students, it's not that it was impossible to do, it is that it was expensive to have interchangeable parts and required a skilling up in the available workforce. Very often, things we like as designers are achievable but prohibitively expensive. Fast forward 100 more years to 1926 and you have Henry Ford in Detroit making 9,000 Model T's per day out of the Highland Park Plant. This solidifies this given belief that standardization makes things cheaper, and often it does unless we pull apart some of these parameters and constraints.

At one point I had the opportunity to be part of the hiring process for a key position in manufacturing at BLU Homes. Through the interviews of the various applicants, I gained incredible insight into a range of manufacturing strategies and the way they might vary between different industries and companies. I remember a story of an employee that was able to do a function in a fraction of the time of what was specified. After investigation, the approach was not able to be carried out by a variety of people nor done in a sustained manner. Mass-production biases reproducibility over speed so that there is consistency.

At BLU Homes we seemed to always be pushing against the promise of the low cost of manufacturing. The mass-production paradigm suggests that prices can drop with enough output - based on the promise of mass-production but at BLU we never found this reduction through volume. The complexities came with what I would characterize as a much broader cultural issue of how people view their house and how they operate when they feel they are designing it. There is a price point at which a client believes they should be able to customize the house and we were building houses which by their nature are expensive. Standardizing the houses meant we could do it faster and cheaper but the market pushed against this, or more problematically, demanded the price of mass-production with the flexibility of mass-customization.

From a manufacturing perspective we tried both a high-tech strategy and a low-tech strategy. In both cases a steel moment frame was the structural "chassis" that accepted variations in program configuration and enclosure (solid walls, walls with windows, or large glass doors). In the high-tech approach we were going directly from CATIA files to rolling our own light-gauge steel framing members, cut and punched, with zero waste. This required a mix of skilled labor and unskilled labor. But the market demands required reductions in cost and time, and BLU transitioned to a low-tech approach that required simplified diagrammatic drawings for unskilled labor to work with traditional materials. This change required reworking the products, engineering, and the drawing process and output to be handed off to manufacturing. This came with a more rigorous process for a bill-of-materials for the purchasing department that included the development of a database and library of all the required parts for assembly tied to the negotiation of contracts for purchasing materials or components in bulk. Again this was an incredible process to be part of, watching the changes in design and collaboration process driven by what I soon realized was a complex manufacturing ecosystem where every aspect needed to be aligned. In the end I don't believe the low-tech system was able to deliver the required price or time reductions either.

To this day I still consider the massive upfront investment required for manufacturing efficiently and I don't know if the long term costs out performed the mass-crafted approach that one finds in architecture where each house is a unique prototype. Over time with enough houses built I am sure this reaches a tipping point but at an early stage of the endeavor we were treating the houses as products long before the entire system had been prototyped.

While the manufacturing was being tweaked, the design team was also tasked with retooling the products to be more manufacturable. One example would be a standard set of window sizes that up until that point had used available sizes from window manufacturers based on a model-by-mode / case-by-case basis. Where the factory had to manage about 50 different window types became more like 10 window types. This allowed storage of windows and bulk ordering discounts that were not feasible previously. Beyond design for manufacturability, the design team also needed to confront the high number of customizations requested by clients. To address these constraints of flexibility and price, we developed packages of finishes and options, like that in the automotive industry. We could pre-design these offerings to make sure they worked with manufacturing and could be supported by market research. As a result our digital parametric models were tied to a client-facing, online configuration tool. With this web based tool, a client could make selections of house plan, kitchen type, finish and fixture choices, walk through a virtual version of the house, and see the fixed price of their decisions.

Sara: *How do you imagine this type of work moving from mass production to mass customization? Architecture is inherently a small run, one-off, mass-crafted approach. Heritage sites are a more extreme version of one-offs and must find a way to leverage mass-customization.*

Karl: The gap between design and construction seems to be closing, in a large part because of the ability for designers' software to communicate with fabricators' hardware. So I believe that the move to mass customization occurs first with design tools. Parametric and algorithmic software help us to conceive of things more as a system instead of as one-offs. If designers can also understand manufacturing or construction processes more fully, we can find opportunities for variations. That deep construction knowledge could lead to mass customization.

Sara: *Part of what I am investigating with my research is the implication of technology on the design process. Can you start by talking about the workflow from design to manufacturing as it relates to the construction process in the US and your experience at BLU Homes?*

Karl: I often reference a simple diagram from *MetaSkills* that illustrates automation on a spectrum. At BLU we developed plug-ins within Revit to automate many of the tasks that were both cumbersome and had accuracy issues. We looked at it from the perspective of the designer (and client) and then automated the required output for the factory. This process was incredibly effective but only works in instances where the process is repetitive. We were customizing products. If one understands the scale of repetition it could be deployed in different ways. We already see this as it related to parametric design and BIM where many of the drawings are extracted in an automated way. The aspects that we took on, were the automation of the floor and wall framing members and spacing. Objects placed by designers would either attract or repel framing members. If a wall switch was located, it required a vertical stud to be placed adjacent to it, while a toilet would require that floor framing members needed to avoid the toilet. On-site carpenters can look at plans and see a toilet and make adjustments but in the factory setting, the responsibilities were separated by manufacturing station so the framing station only needed to know where the structural members were placed. This would be an example of where the infrastructure behind the scenes is customized based on client choices. Through our automation, we were able to make these customizations without any schedule or budget implications. It's minor, but it would be an instance of a small scale aspect of mass customization from my perspective.

Sara: *Talking about process innovation: the first industrial robot was used in 1969 at General Motors. In 50 years we still don't see a tech transfer in our sector. Do you have a sense of why this might be?*

Karl: I would see at least five reasons why. 1. Robots have been expensive but the prices are coming down. 2. The technical knowledge to run them has been high. 3. Predominantly they have been used in repetitive tasks and construction seems to be structured in a different way. 4. The construction industry is fragmented. 5. The construction site is not set up for what we understand as industrial robots, currently.

There are responses to all of these. LTU has been working with Ballard International. I see Ballard as a very unique inflection point in the Fourth Industrial Revolution. They buy robots wholesale from the automotive industry, make sure they work, and resell them to different industries that can access these technologies with less investment. People are coming out of school with more of this knowledge as digital fabrication has recently embraced robotic fabrication. In the same way that digital fabrication led the change from mass production to mass customization, the use of robots in school for prototyping will make them more adapt for more non-routine tasks. Introduce sensors on the robots and it will be even better. There is a 100,000 architects in the United States and 20,000 architecture firms. This means there is very little consensus. It also means that there is very little venture capital because of this distributed and fragmented market. While the construction industry has a high revenue, it is split among almost 700,000 contractors. This means that if someone wants to revolutionize the industry, it's difficult to do because it is incredibly localized. In industry, much of the automation is for simple / single purposes, where you can justify automation advancement of one step in the process. Robots are interesting because of how flexible they are. But it's a bit of a paradox because while they could serve many functions, it hasn't' been proven of how well they could solve one problem really well on a construction site.

Sara: *In the 70's, some big construction companies experimented with single tasking robots on-site but it seems that this didn't have a continuation. Robot programming was also used to differentiate the tasks that a single robot could perform. This was a way to pioneer the customization of production which is an ongoing conversation today. What are the drivers that stopped that disruption in construction to happen? Are we at a changing point now?*

Karl: Construction is in the business of customization. Every building site is unique. Every building built has some level of uniqueness. Given how unique buildings are, the industry is set up in an individualistic basis. Actually, I think this is problematic. I'm not sure that the automation disruption in construction ever started. The industry is set up to deal with individual clients, many of whom have never been a client before. Every building built is a one-off prototype. Our industry suffers because it is very common for buildings to be over budget and behind schedule, and these are two things that mass production has been able to deliver. This puts the perception of our industry at a disadvantage. The question could be: can we deliver customization with reliability? Means and methods are convention but their deployment seems to vary. What are the construction tasks that might be turned into standard routines as a means of increasing our performance or our reliability? Architects have long complained about the quality that results from the construction industry and now because of digital design one could imagine that architects can pre-simulate the construction process. Architects might be in a great position to introduce robots into the process because of the design tools at our disposal.

Sara: *I came across the European Document euRobotics, the strategic multiannual research agenda 2014-2020 for robotics in Europe. The document is detailed and it foresees future developments and timelines for the application of robotic technologies in different sectors.*

Karl: Which sectors do they highlight?

Sara: *Medicine, surgery, agriculture, and assembly. Is there a chance to get designers to be early adopters of technologies?*

Karl: Sadly, probably not. Which is only to say that culturally we value the longevity of buildings and contractors bear the risk if a building does not perform. This means that the construction industry will probably never be the early adopter that you want it to be. But in my digital fabrication class I loved to draw connections between the furniture that Frank Gehry designed, to the bus stop that he designed, to the Fish sculpture, to the buildings. One can take on different levels of risk and innovation with different scaled projects. I used digital fabrication in many restaurant interior projects that never had to deal with enclosures. So I could investigate ideas about non-standard parts, while not having to worry about waterproofing.

Sara: *Similarly, in my dissertation I argue that existing building as a test case before moving to something with more value as Cultural Heritage. One last questions: did BLU Homes consider using robots?*

Karl: This is a very good and complicated question. So first I would say that I fishinished working with Blu Homes in 2014. At that point I went back to teaching full-time and one of the classes was an *Introduction to Robotic Fabrication.* So I have to admit that I didn't have robots on my brain until that point in time. But back to Blu Homes, Blu did experiment with digital fabrication tools and file-to-factory processes at an early stage in its development. Those technologies had to do more with components and sub-assemblies than the actual assembly. So while I could imagine some of the work in the factory being carried out by robots, I think the economics might have been the hurdle. We located our factory in a geography where there was a large pool of motivated and experienced workers. This pool was large and meant that the cost of automating would always be more. Your question is complicated also because geography, time, and many external factors might govern when is appropriate or cost-effective to deploy robots. I know of many markets where labor is scarce and robots may arrive there sooner. I usa an example of a unique Dairy Farm in Northern Michigan that uses robots to milk their cows, mainly because they can't find anyone willing to do that work. We will continue to watch in which industries robots pop up and it's probably determined by the complexity of this type of equation.

Sara: *I'm incredibly interested in this because the restoration market is both a premium skilled labor and an aging population of craftspeople. Which is why I believe robots are an important next step in the evolution of Cultural Heritage. Thanks for taking the time to discuss this issues.*[1]

1 The interview took place at LTU-CoAD, MI, USA, on May 03, 2019.

3.2 Pioneering on-site building automation

"Industrialisation of buildings seems to be the keyword, in which direction the building industry has to develop. In our technical age houses should arise like products in a factory. The engineered work of 'house production' is most distinctly possible in a factory. But also the building site can largely be attuned to it [Günther Gottwald, 1951]

Since the early days of assembly lines, multiple proposals for automated housing construction have been attempted (Keating et al., 2014). One of the first historical examples dates back to 1917, when Thomas Edison patented a single-pour concrete system to build standardized houses, by using a reusable mold. The idea anticipated what in the 1920's and 1930's was called "industrialized construction process", which is a shift from serial prefabrication of building components to the mass production of a standard house.

Industrialization influenced the work of modernist architects, forcing designers to think differently about the aesthetic values of buildings as products, buildable by using new machinery, serial-produced technological units, and industrially fabricated materials. The aesthetic shifts accordingly with socio-economical changes. The minimalism of the 1920's was accompanied by the dualism of cheap materials - expensive labor. The post-war period on an international scale determined that the cost of materials was higher than the cost of labor. With the Second Digital Age, the formal possibilities determined by digital fabrication lead to a rediscovery of compositional and decorative complexity.[2] In relation to market value, today the cost of skilled labor (less and less available in the construction sector) tends to rise gradually as automation equipment such as industrial robots cost reduce. The implementation of digital technology in the building site is a subject that began between the 1960s and 1970s, to deliver an idea of modernity and at the same time to exploit the technological potential for the management of dimensional tolerances. At the same time, the use of robots on-site was an attempt to "reduce the number of stages involved in construction, to increase the employment of unskilled labor and to shorten the completion time" (Bock and Langenberg, 2014).

The idea of pioneering building site automation, is rooted in production processes changes that took place with the First Industrial Revolution. The development of infrastructures, especially in Europe, initiated an increased mobility over countries, of industrially produced materials (cast-iron brams or glass), craftspeople, building knowledge, and local traditions. The Crystal Palace for the World Exhibition in 1851 is a project that represents the synthesis of this change (Nardi, 1980). Standardization has been the key to making mass-produced elements economically viable for the construction of large buildings.

2 The concept of digital complexity was explored by Benjamin Dillenburger with the project "Digital Grotesque". Another example is the work "Quaquaversal Centrepiece at the Spring-Summer 2016 Iris Van Herpen ready-to-wear-collection" where robotic arms 3D printed and manipulated a dress. The project was carried out by Iris van Harpen, Jolan van der Wiel, and Marjian Colletti + Rexilab.

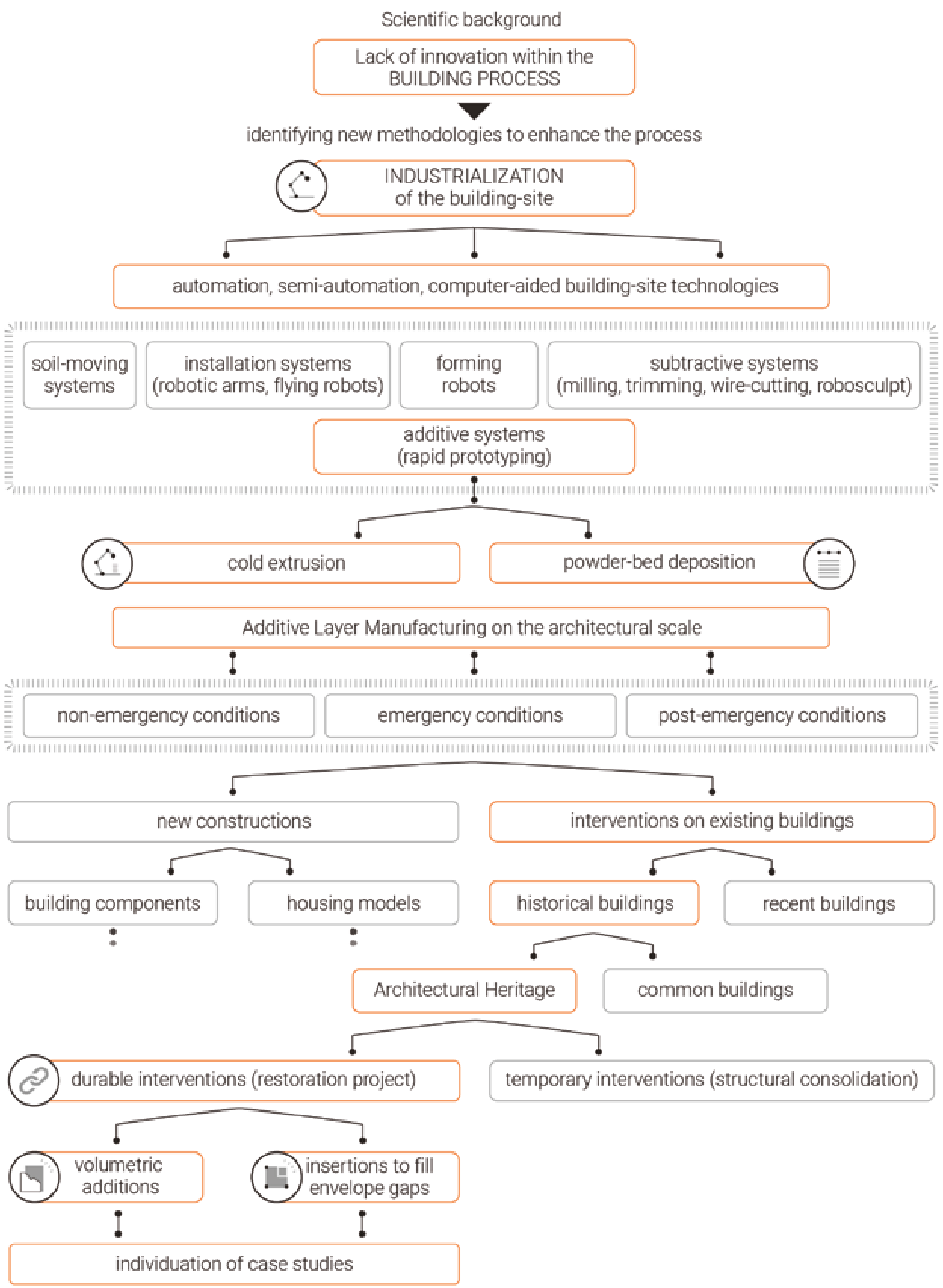


Fig. 3.1 Investigation of the topic: industrialization of the restoration building site. The production of building products can be optimized by exploiting tools and knowledge of the Fourth Industrial Revolution.

The same approach as "design of a limited number of identical building elements to construct slightly different housing type enabling serial mass production" (Bock and Langenberg, 2014) was decisive in tackling both the post-war housing crises in Europe and the subsequent economic boom of the 1950's-1970's.

Before contingent events forced several countries to respond to the post-war housing demand that corresponded with a wide population growth, numerous experiments were carried out on prefabrication of building products. The aim was to turn built architectures into industrial products. However, these experiments were not supported by a shared agenda to envision the success of the proposed methodology. Some speculative exceptions to the trends were conducted by avant-garde architects. The Dymaxion House, designed by Buckminster Fuller was a futuristic project that was completed in 1930 to revolutionize techniques and materials for building constructions. The flat-pack lightweight houses designed in the 1940's by Jean Prouvé were prototypes realized to be shipped worldwide and easily assembled on-site. The Packaged House System of Konrad Wachsmann and Walter Gropius was a prefabricated modular construction system designed in 1942 with the aim of exploiting the full potential of standardization and assembly. A larger-scale attempt was made with Operation Breakthrough in the United States with the promise never kept to give home to 26 million families between 1968 and 1978.

In the Italian framework, in the post-war scenario that took place in the 1950's and 1960's the concepts of standardization and modularity gained ground. Professionals were interested in "unifying construction materials and defining projects that were studied in all their executive details from the beginning" (Arbizzani, 2015). The objective was to extend the methodologies of industrial production to the construction sector. This approach was called "closed prefabrication". It advocated for rigid serial production to reproduce technological units in a cost-effective and predictable way. It was based on a limited use of materials to make components that deskilled labor could assemble and install. In the 1980's, a period of strong technical experimentation, the culture of construction moved toward experiments no longer based on the industrialization of the projects as a whole, but on the "elaboration of techniques for the programmed and controlled on-site construction of building parts. It lead to a renewed notion of building system and flexibility" (Arbizzani, 2015). This methodology was called "open prefabrication". It is based on the use of open components, available in catalogues and compatible for fast assembly. This approach allowed for variations in production, enabling designers to work with greater design freedom on materials and components.

The Italian 1980's were a period of decisive theorizing. To begin with, in the publication *Progettare nel Processo Edilizio*, edited by Mario Zaffagnini, Pierluigi Spadolini systematized building construction dividing the production of the technological units into three categories: industrial, semi-industrial, and craft (Spadolini, 1980). In addition, Ivan Cicconi specified that there were two solutions for building industrialization, prefabrication and on-site industrialization. Prefabrication was the production of building components before entering the construction site. On-site industrialization consisted of the construction of units directly on construction sites. Prefabrication could be heavy or light. Heavy prefabrication used traditional materials such as concrete or aggregates. Light prefabrication consisted of the use of industrial-derived materials such as steel and petroleum-based derivates (Cicconi, 1981).

In those years, the drive for innovation led to the use of the climbing formwork. It was a hydraulic system that allowed the industrialization in situ and pre-tempore automation of the construction site phases for high rise buildings. The first example in Italy of the integral use of this technology was carried out by Mario Zaffagnini. Through his work, the climbing formwork, one of the strongest limits to the designer's expressiveness and spatial typological flexibility, was brought into the architectural discourse. Unfortunately, this benchmark was not followed by other disruptive changes.

The race for automation on the construction site happened between the 1960's and the 1980's in countries that invested the most in technological advancement. In the 1970s's there were opposing trends in the economies of Japan and the United States that are worthy of analysis. In 1973, the oil embargo in the USA triggered recession. The awareness of limits on economic growth arose. Therefore, attempts to fully industrialize the building process declined or were abandoned in both Europe and the US. Simultaneously, in Japan the growing population led to an incremental demand of social housing. The lack of skilled labor in the building industry was a driving factor to lead the promotion of automation in prefabrication and construction. It was an alternative to traditional construction practices. As Thomas Bock and Thomas Linner explain in the publication *Changing Building Sites: Industrialisation and Automation of the Building Process*, in the Japanese context a massive research was directed towards:

- automated housing prefabrication;
- on-site single task construction robots;
- integrated automated construction sites.

In the 1960's, Japan shifted from the building site to a structured and automated factory-based work environment. Where 85% of the work was executed off-site for the most part by human labor. The processes still relied on the assembly line, rather than real automation. In contrast with European approaches, where prefabrication was primarily optimized to achieve fast and cheap production of large numbers of identical elements, Japanese prefabrication was more oriented to customization and personalization. The assembly-line work, combined with the advantages of human labour in a factory, "allowed for the individual adaptation of single parts meeting customer demand without disturbing the production chain. They could be taken out of the assembly line and replaced manually, to be reworked or finished, before being introduced back into the next stage of the production process, causing minimal disruption to the overall productivity" (Bock and Linner, 2014). This approach can be considered a precursor of today's promotion of robotics in architecture.

The enhancing of research in this field during the following decade was based on the 'robot boom' in the manufacturing industry. As a consequence, the adoption of robots was a logical approach for Japanese construction firms. Single task construction robots were subsequently developed. They could execute a single, specific task repetitively. They could be used on construction sites for demolition, surveying, excavation, paving, tunneling, concrete transportation and distribution, concrete slab casting and finishing, welding and positioning of structural steel members, fire-resistance and paint spraying, inspection, and maintenance. Sites would be structured and designed like factories. The final objective was the implementation of automated manufacturing and construction technologies.

Hence, research in construction automation was escalated in Japan, leading to the development of integrated automated construction sites.[3]

In the 1980's there was a technological reorientation from single-task construction robots towards integrated automated construction for larger structured environments.[4] As professors Bock and Linner describe, these integrated automated construction sites were organized "as partly automated, vertically moving on-site factories providing a shelter for on-site assembly, which was controlled, structured and systemized, and unaffected by the weather, as well as for a disassembly process of prefabricated, modular low, medium and high-level detailed building components" (Bock and Linner, 2014). Therefore, robot technology was facilitated by the creation of the right simultaneous conditions to install automated cranes, computer vision systems, and real-time control equipment. In this context, the idea of climbing formwork previously experimented in Italy becomes a climbing system, or sky factory.[5] It can be described as a "automated/robotic on-site factory used especially for vertically oriented buildings" (Bock and Linner, 2016). This system allows to rise the working environment while a floor level is complete. The positioning of building units by manipulators and actuators. Japan's contractors have developed partly automated deconstruction systems, which follow in reverse the same approach as the automated construction sites, to reduce noise, dust, and disturbance of the surrounding environment.

Technology has evolved substantially since the 1970's-1980's. The design industry has not. Some of the world's largest firms still do everything on paper from managing blueprints to keeping track of employee hours and pay. The past efforts of automating construction failed for several factors. First of all, the robotic application described above required high initial installation costs. For this reasons, the integrated automated building sites were used when contingent conditions required them, such as high labor cost, traffic, noise, and waste restrictions. Moreover, these efforts failed because computing power was still weak (Fig. 3.2, Fig. 3.3). Finally, there was a lack of regulations. The historical precursors show that the implementation of robotics in architecture at a large scale requires a substantial change in the early design stages as well as in the construction process that goes far beyond imitating existing building technologies. Instead of trying to copy and perform factory automation methods, new robotic tools require: appropriate conditions, design strategies, kinematics, programming, and control. Every innovation in construction technology needs at least one generation to establish itself.

Advances in automated construction continue to be developed today. The use of flexible industrial robots in the prefabrication of building elements, as well as in architectural research institutions, is becoming widespread. Now the technological and economic accessibility foundations are being laid.

3 An example of single task robot is the Z-Hand vertical delivery system for transporting material for interior finishing. The system was developed by the company Kajima.

4 An example of integrated automation is the SMART system by the Shimizu Corporation. It embeds pick-up, vertical delivery, and positioning processes.

5 An example of sky factory is the Akatuki 21 system, developed by Fujita for the construction of steel-based buildings. It manages material delivery, logistics, and joining of building components.

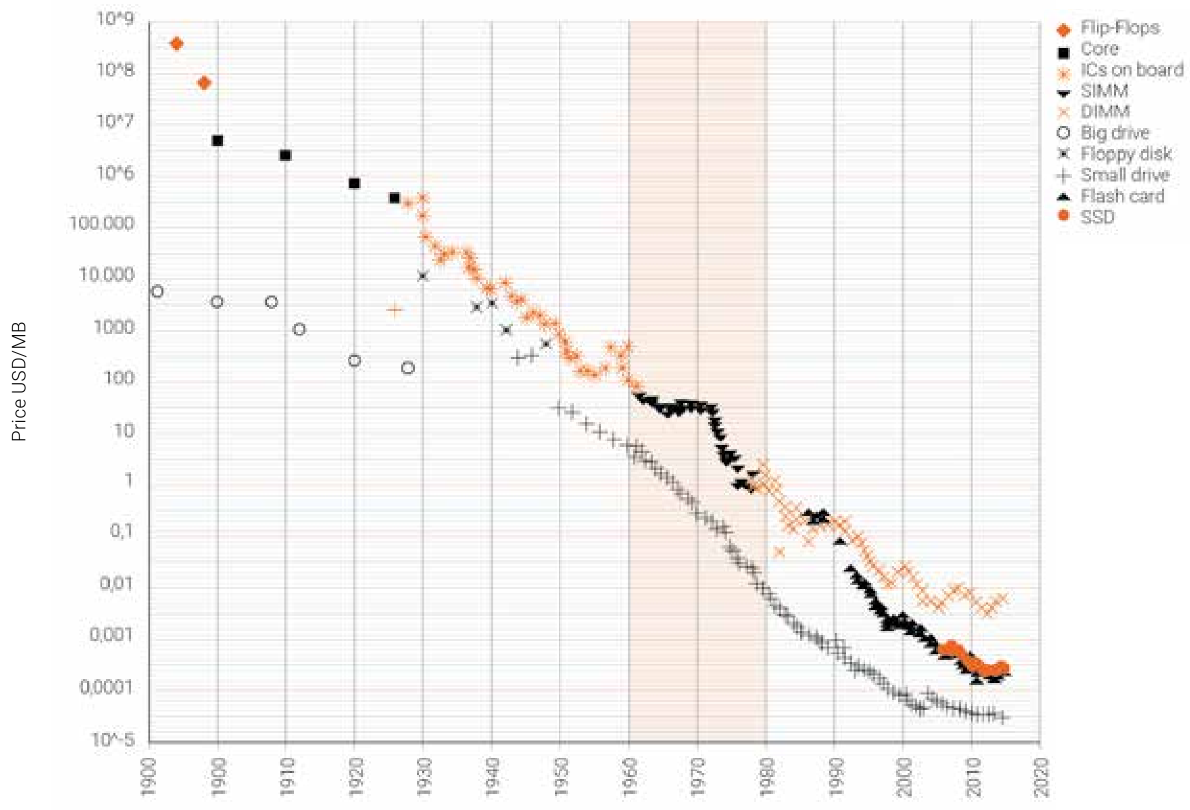


Fig. 3.2 Historical cost of computer memory and storage. Source: https://hblok.net/blog/posts/2017/12/17/historical-cost-of-computer-memory-and-storage-4/. Between the 1960's and the 1980's, 1 MB used to cost around 50 dollars. A gigabyte was worth 50,000 dollars.

Fig. 3.3 What 5MB of data looked like in 1955: 62.500 punch cards. Programmer standing next to the SAGE computer's control program. Source: the Computer History Museum and the MITRE Corporation. Available at: https://kiranbot.com/post/2016-07-27-punch-cards/.

Briefly, in the academic and industrial research sectors, there are some main approaches for on-site robotics:

- **large-scale automated systems, or contour crafting;**
- **cable suspended platforms;**
- **swarm approach;**
- **multi purpose robotics;**
- **mobile robotic units;**
- **folding systems.**

The **contour crafting** system was theorized by Behrokh Khoshnevis from the University of Southern California. It is a bridge structure that moves horizontally along two parallel lanes. The translation of an actuator is controlled in cartesian coordinates. The focus is to produce an entire building through the construction of full-scale components on-site (Khoshnevis, 2004). Moreover, the **cable suspended platforms** are "automated systems where multiple cables are attached to a mobile platform or end-effector" (Sousa et al., 2016). The might be considered as a "precise crane" (Dubor et al., 2018). The Italian company WASP uses this approach for the construction of full scale building created through additive manufacturing. In this case, the end effectors can extend or retract in a fully automated way. The **swarm approach**, instead, advocates for the use of small automatic units that are programmed to perform a collaborative behaviour for the achievement e collective goal. It includes the use of flying autonomous vehicles to manipulate building components in the air. It has the potential of avoiding ground-based mobility issues and the need for cranes. An example is the project Flight Assembled Architecture realized at ETH in 2011 (Wilmann et al., 2012). Back to ground systems, **multi purpose robotics** or robotic arms are flexible machines that can be programmed to perform autonomous tasks without human intervention. Their kinematics consists in polar rotations of axis. Robots work by using actuators, or end-effectors, which can operate following an additive, subtractive, smart assembly, or combined logic. In more sophisticated terms, the **mobile robotic units** are machine that can operate in a dynamic way. They are installed on movable platforms and may reach inaccessible locations. An example of mobile robotic platform was developed at ETH for the construction of the Dfab House (Dörfler et al., 2019). Finally, **folding systems** are machines that can reshape construction materials at the architectural sub-system scale. The next real change will only occur on the construction site once design, management and engineering comply with the robot as a new tool. The next real change will only occur on the construction site once design, management and engineering comply with the robot as a new tool.

3.2.1 Feedback-loop strategy

The building site is a complex and dynamic workspace. The automation machines that best fit into this context are those able to visualize and interpret the surrounding environment. These actions are possible by adopting the feedback loop strategy or robot sensing. It consists of the integration of tools that expand the robots' sensitive capabilities. The tools are sensors and computer vision systems that tie robots, humans, and materials with a nonlinear workflow, driven by a flow of information coming from external inputs. The feedback loop methodology is the main innovation that will allow for robotics in the building industry and architecture. Each time the system conditions change, the robot can readjust its movements in order to achieve a predefined objective. In other words, as the conditions of the surrounding context change, the programming functions vary accordingly. The optimization of the results always remains the priority.

The feedback loop relationship system is particularly useful for additive manufacturing, as it is a process that "comprises a complex ecology of interactions between a diverse set of parameters, such as the characteristic of the material, the rate of material flow from the extrusion nozzle, the rate of cooling or curing of the material, and the structural capacities" (Sutjipto et al., 2018). Moreover, human interaction, including design interaction, with the sensors allows the exploration of "a new framework where a craftsperson intuition and sensibility can be combined with the power of digital analysis and the precision of robotic fabrication" (Dubor et al., 2016). An example of adaptive human-machine interaction through robot sensing is the project The Endless Wall, developed at the ETH at Gramazio and Kohler Research.[6] A robot programmed to do pick-and-place of bricks for the construction of a wall updates its toolpath following the instructions given in real-time by an operator who changes the target points in the physical space. The sensor system provides input information to the software that generates a new algorithm by providing the machine with new instructions to execute. Nowadays, companies like Kuka, given the possibility to open a market for on-site robotics, is doing research on the development of lightweight robots, mobile robotic platforms, and waterproof robots (Shepherd and Buchstab, 2014).[7] As explained in the experiment "Material Feedback in Robotic Production", published in Rob|Arch 2014 (Raspall et al., 2014), a robotic sensing workflow may be structured as follows:

- feedback signal by sensors, which gather information from the physical world;
- control protocols that define how instructions are adjusted in response to new inputs and accordingly with the production sequence;
- online machine operation that allow new calibrated instructions to be sent to the robot, as digital parameters;
- compatible information platform used to ensure a consistent flow of information.

The feedback loop strategy is identified as an operational tool in cyber-physical robotic systems (Menges, 2015). It allows robots to be used as adaptive and responsive design units. This design methodology makes it possible to manufacture complex material systems that are difficult to predict through digital simulation, due to the nonlinear relationship between material, manufacturing tool, and external parameters (Brugnaro et al., 2019). The inclusion of dimensional tolerances within the digital fabrication process represents the definitive convergence between the predictable digital world and the unpredictable physical reality. This type of nonlinear interaction can be seen on conservation sites as layers are uncovered.

6 The Endless Wall, developed at ETh Zurich by Gramazio and Kohler Research: https://gramaziokohler.arch.ethz.ch/web/e/projekte/216.html.

7 Some examples of Kuka on-site robotics are: Kuka LBR iiwa lighwight robot with seven axes, the Kuka omniMove, and the waterproof Kuka Kr Agilus Wp.

3.2.2 Cobotics on-site

The scientific community agrees that, in the next decades, scientific research will address issues on cobotics and on-site robotics. In particular, cobotics means human-machine collaboration in a shared physical workspace. The term comes from the paper "Cobots: robots for collaboration with human operators" by Northwestern University professors Edward Colgate and Michael Peshkin. In 1996, for the first time, they described their prototype of a cobot or collaborative robot. It is described as "a robotic device that manipulates objects in collaboration with a human operator" (Colgate et al., 1996). Cobots are tools designed to communicate with people by sharing the same workspace. Cobots operate at low speeds and are equipped with sensors that allow them to detect obstacles, to enable safe collaboration. These tools were developed to advance intelligent automation and overcome the idea of robots as "obedient slaves" (Picon, 2014) that work "autonomously, automatically and in a reprogrammable way on three or more axes for use in industrial automation applications" through the installation of a fixed or mobile multi-purpose actuator. As Paul Daugherty and James Wilson point out in their publication *Human + Machine: Reimagining Work in the Age of AI* unlike robots, "cobots are designed to work closely with people" in a scenario where "manufacturers are able to re-imagine previously static processes and workers, interacting with intelligent machines, take on new roles that allow companies to make more varied and adaptable choices" (Daugherty and Wilson, 2018). This approach is part of the logic of Digital Transformation and represents an operable methodology to address the progressive loss of labor and skills that is occurring in the construction sector, following the crisis that damaged global markets in 2007. Moreover, from a theoretical standpoint, through cobots, "the exclusive dialogue between designers and robots are not anymore the only development worth exploring. The human workforce will not be missing from this narrative anymore: "imagine a unified design and fabrication process based on a series of conversations between men, designers, workers, machines, computers, and robots. A truly different architecture could arise from such extended conversations" (Picon, 2014).

3.2.3 Augmented Reality for building construction

Augmented reality, which is the overlapping on the physical reality of digital layers, in the future, could represent a useful resource to be used on-site. The company Fologram developed an AR system that allows workers to follow instructions to build a parametrically generated wall.[8] In doing so, the bricklayers wear glasses that visualize in real-time the footprint of the bricks that need to be laid, in logic order. The augmented reality building strategy provides digital instructions to workers, turning them into digital craftspeople. The methodology might be applied for non-manual site tasks, such as excavations, installation of formworks, or casting of concrete slabs. A similar approach was used within the European project BIM4placement, where operators during excavations could execute commands dictated by software to perform only the ground movements necessary to achieve the result. Sub-task time-wasting was avoided. Human-machine interaction through AR stands between manual processes and fully automated systems. Among them, building site autonomous vehicles

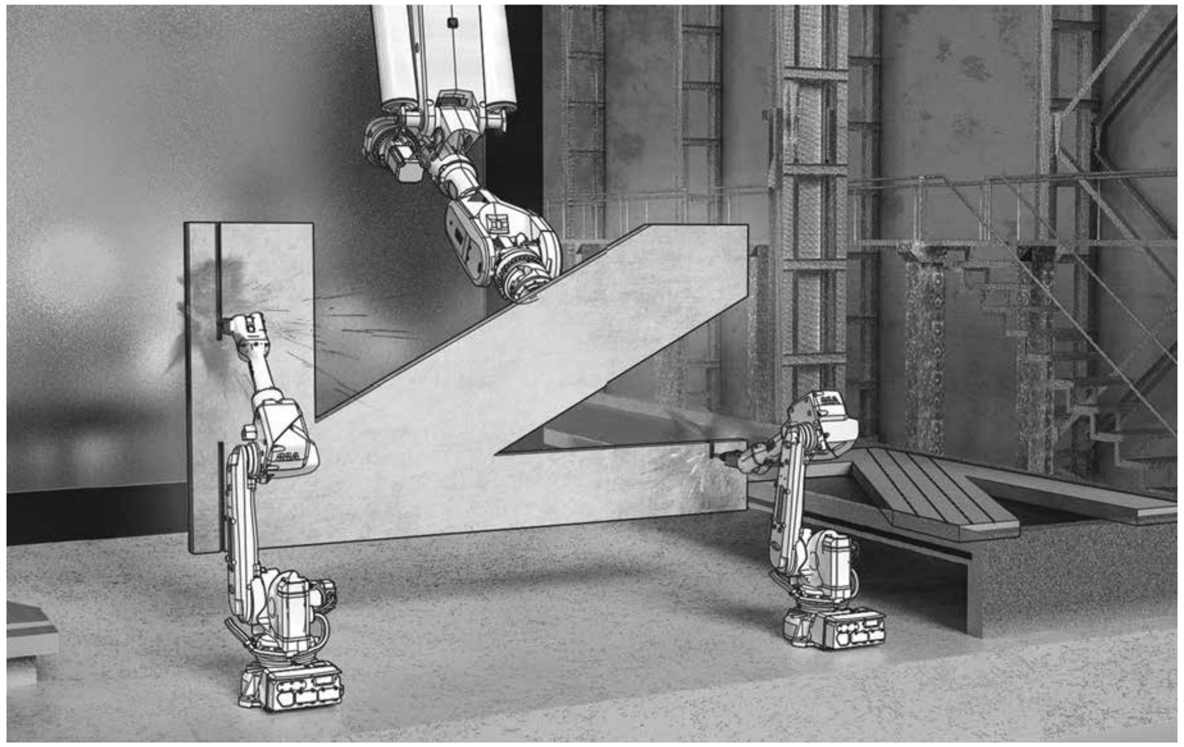
8 Fologram Talks: Holographic Brickwork: https://vimeo.com/305901280.

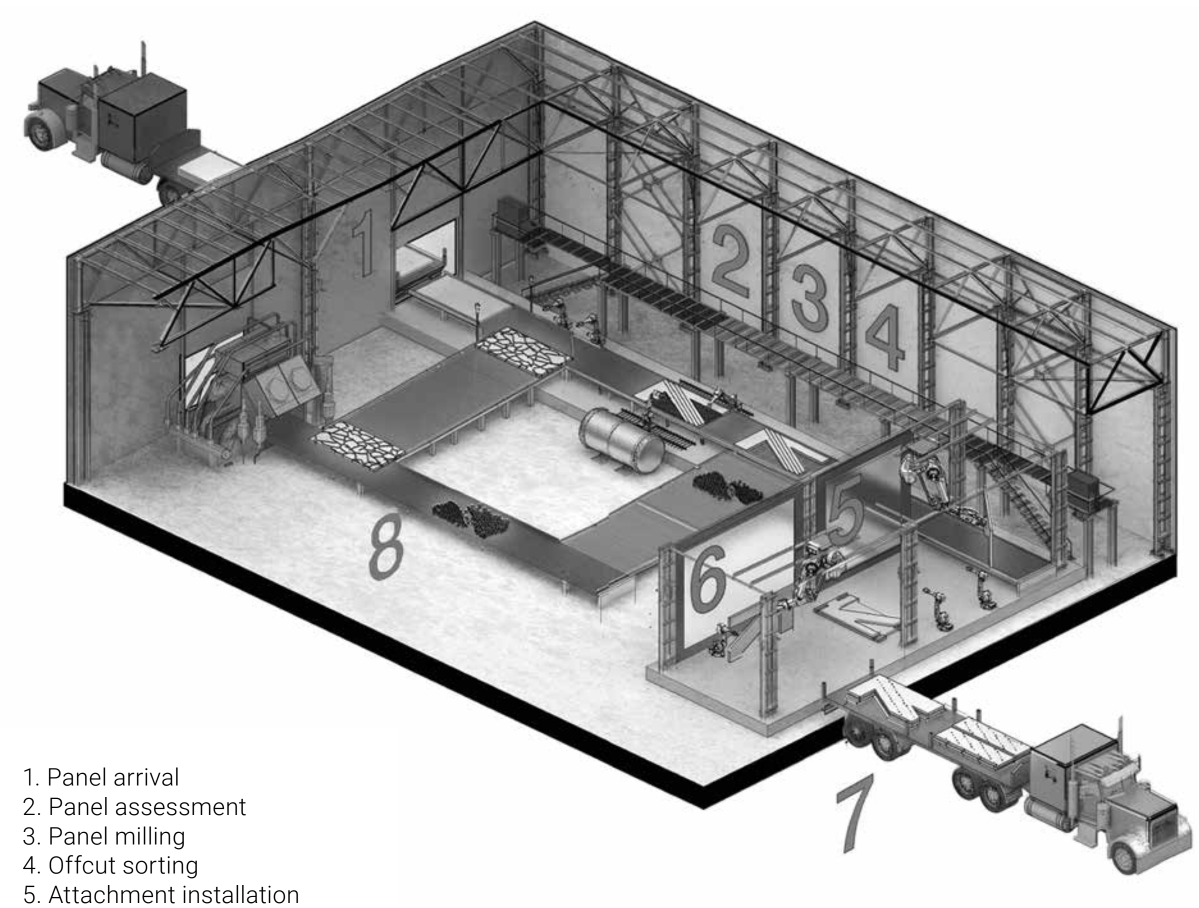
are included. Currently, the working group at Gramazio and Kohler research is working on the most prominent augmented reality on-site construction brick facade for a winery in Greece. The timeline expected for the completion is three months. AR allows workers to place bricks following a custom made dynamic optical guidance, which includes inertial-object tracking in space, to create a sophisticated design. The project looks like a research continuation of the iconic Winery Gantenbein that, in 2011, opened the way for full-scale digital robotic prefabrication. The higher-education sector is embracing the innovations. Virtual Reality 3D modeling classes are starting to get into international curricula. Gravity Sketch, to mention one, is a software that allows inserting body gestures in the early-stage phase of the design process. In this design environment, operable by using a headset and handles, two-dimensional drawings are not needed. The conceptual work is implemented from the very beginning in three-dimensional space. The design mode has some similarities with robotic programming, for which the definition of kinematics for the achievement of the outcome is a fundamental part. The development of upstream skills will allow better communication with operators downstream of design processes, integrating design and implementation in a common cyber-physical-digital workflow.

3.2.4 Artificial Intelligence integration

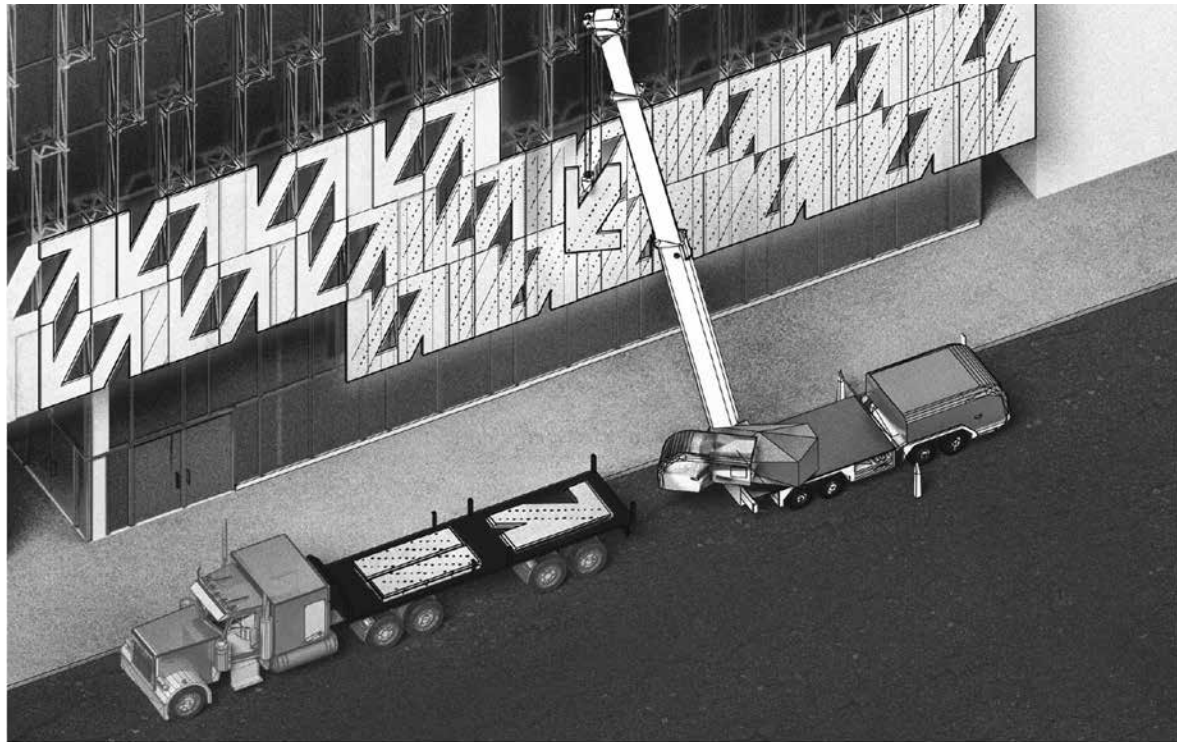
Scientific research is developing working environments suitable for human-machine interaction. In the construction sector, a new generation of robots can be used for operations on-site or digital prefabrication off-site. The robots could be integrated with AI algorithms that expand physical abilities, they can extend cognitive capabilities too. This design scenario is based on the use of sensors that can acquire data in real-time and a computational process that adapts the actions of the machine in an intelligent way creating a direct connection between digital model, environment, and physical output. Borrowing Mario Carpo's words in *Fabricate*, "in a sense the first phase of the Digital Turn reversed the industrial revolution, eliminating the need for mass production, standardization and economies of scale. Artificial intelligence now suggests an almost pre-scientific intuitive approach to making" (Carpo, 2011). Paradoxically, the use of AI eliminates the need to gain experience of a phenomenon, as the computational power could predict the effects in a machine-like mode, without the need for empirical evidence. This approach is a step towards the increasingly established post-humanism (Hayles, 1999), for which we inform the machines and then receive optimization feedback from them. In this context of defining the state of the art, two research projects that can help to refine AI, also for robotic applications, are mentioned. These projects are ImageNet and Robonet[9], promoted by Stanford University. The purpose of these projects is to build a vast database of images catalogued according to a specific hierarchy. These images can be used for machine learning and therefore AI implementations. In this way, robots can be instructed with precise data packages, depending on the workspace where they are to be installed. The machines can then be informed for the recognition of site data and images. They will be able to predict hazardous conditions or contribute in the design phases through continuous feedback between architects, programmers, and builders. This metholodogy could be useful especially in conservation building sites, which contain a large amount of unique information.

9 ImageNet: http://www.image-net.org/.. RoboNet: http://ai.stanford.edu/blog/robonet/.





1. Panel arrival
2. Panel assessment
3. Panel milling
4. Offcut sorting
5. Attachment installation
6. Panel treatment
7. Panel installation
8. Concrete recycling



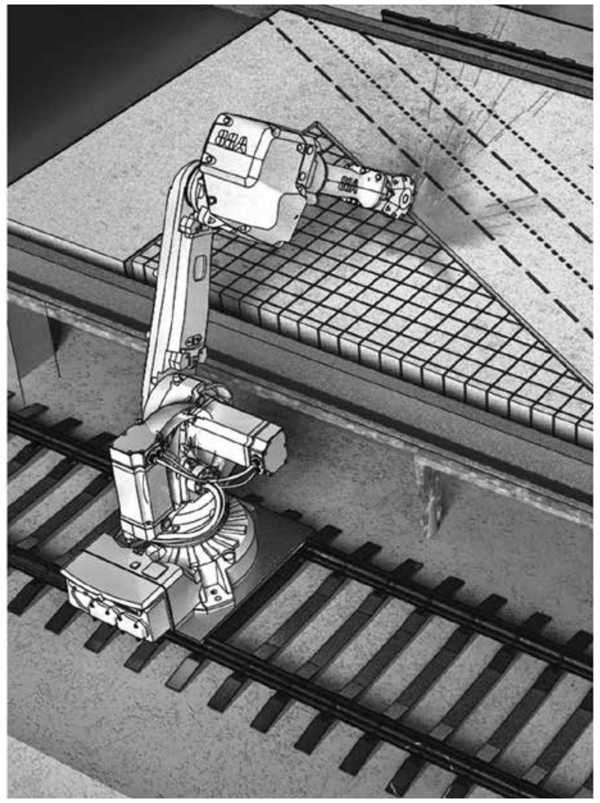


Fig. 3.4 The robotic construction site as it could be within the next decade. Source: *[DESIGNING OUT WASTE] A brief on robotic refabrication.* The publication is a the outcome of the inaugural FPInnovations Scholar-in-Residence program at the School of Architecture Planning + Landscape (SAPL) at the University of Calgary.

3.3 From data to matter: large-scale additive layer manufacturing in construction

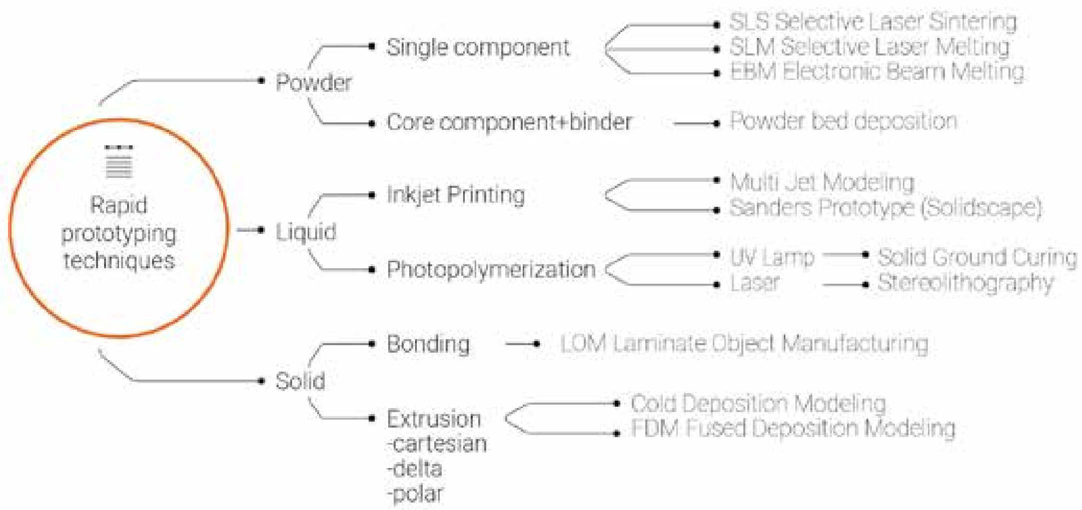
"Although today's digital manufacturing machines are still in their infancy, they can already be used to make almost anything, anywhere. That changes everything [Neil Gershenfeld, 2012]

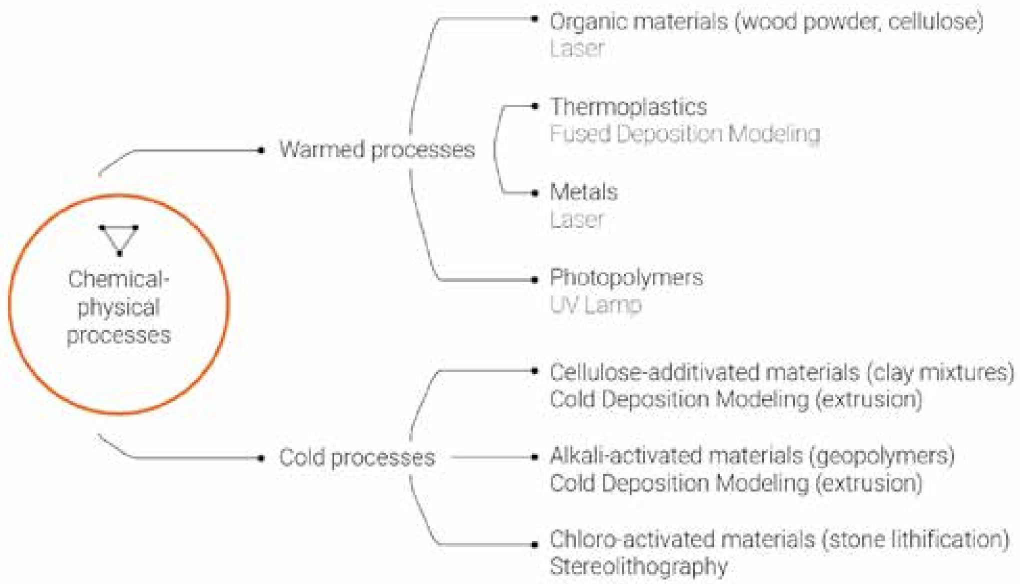
The development of digital technologies in building processes is a need expressed by professionals to interface with each other through a common language, reduce uncertainties, and ensure awareness in design choices. The shared goal is to guarantee the quality and efficiency of the result. At the same time, there is an emergence of new technologies for the production of material components. They are capable of reading digital data, interpreting and reproducing their spatial characteristics, opening up new languages that require technical experimentation and testing of applicability (Gershenfeld, 2012). In order to overcome the standardization of the industrialization of the building process, several innovative systems for site automation have been analyzed. Among them, there are the Additive Layer Manufacturing technologies. Their definition is often approximated to 3D printing, which is instead a subset. ALM allows generating volumes through additive processes by superimposing consecutive layers of material until the finalization of the result, previously digitally modeled. 3D printers are capable of supporting the leap in scale from the design object to the building component. They suggest the possibility of getting away from the design limits imposed by traditional production systems. These technical possibilities initiated the elaboration of constructive hypotheses whose expressive language is based on mathematical models, also deriving from the close scale analysis of nature (Willmann et al., 2013). The latter provides examples of how to optimize the use of resources and the performance of the material.

Additive manufacturing[10] was invented in the 1980's in the United States. It set a continuation of digital CAD (computer-aided design) towards the physical CAM (computer-aided manufacturing). The first AM system to be introduced on the market was stereolithography. It was officially launched in 1986 by Chuck Hull, founder of the company 3D Systems. At large, AM techniques may be catalogued as powder, liquid, and solid-based (Fig. 3.5). Afterward AM processes can be identified according to the material used (Fig. 3.6) or the technical characteristics of the machines (robots or 3D printers) involved (Fig. 3.7). The additive processes involve the materialization of the virtual model through a direct connection between a digital interface and a machine. The connection is made through software that allows the definition of the parameters that inform the production process. The software also gives geometric characteristics to the three-dimensional model, such as thickness, layer height, level of detail, and surface quality.

Today there is a turnaround in the ALM development, which in the early days was mainly used for rapid prototyping. Given the potential offered by additive digital fabrication techniques, the large-scale ALM is a field of investigation for product innovation, i.e., the study of materials and workflows

10 ISO/TC 261 definition of "additive manufacturing": https://www.iso.org/committee/629086.html.





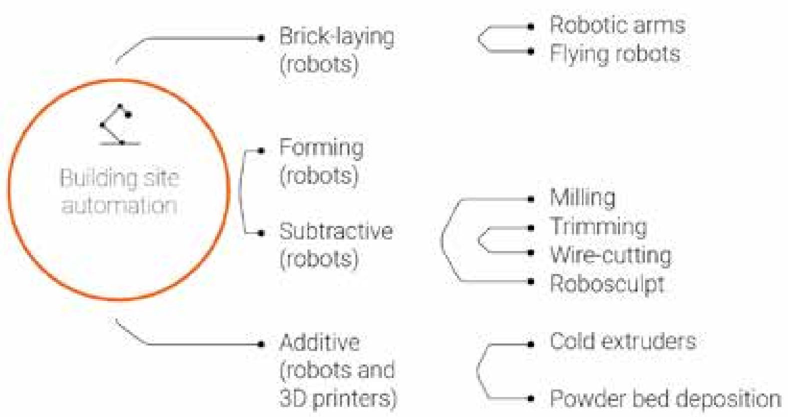


Fig. 3.5 Rapid prototyping classification. This technology can find application within the construction industry.
Fig. 3.6 Materials usable for additive layer manufavturing.
Fig. 3.7 Automated building construction technology.

for building components, rather than for the development of prototypes. The opportunities defined by additive production include the possibility of:

- using the material only where necessary, reducing resource consumption and waste. These materials are generally concrete, clay, or powder-based;
- realizing complex morphologies based on dynamic algorithmic models;
- extending the design time to optimize the result and perform predictive verification models;
- shorten the production chain of construction units;
- simplifying the installation and assembly phases of building components;
- managing dimensional tolerances with nearly industrial precision.

At the same time, this production methodology has limitations such as:

- the management of the work area, for 3D printers, or the work cell for robots;
- the lack of widespread experience in large-scale on-site production;
- the lack of a reference regulatory framework for digital manufacturing workflows and for the implementation of high-engineered experimental materials.

In the current state of the art, ALM can be applied to create technological units or small architectural systems. Large-scale ALM technologies are divided into:

- powder-bed deposition or 3D printing (the programming is matrix-based);
- cold extrusion or 3D plotting (the programming is toolpath-based).

Powder-deposition systems consist of the release through nozzles of alternating layers of a base material (usually a fine inert material such as sand or gypsum) and an inorganic binder that help the aggregates to solidify. They generate monolithic volumes in free form, without geometric limitations on any axis (Kestelier, 2011). In 2007, using this technology, the Italian company D-shape,[11] in collaboration with Shiro Studio,[12] created Radiolaria[13] (Morgante, 2011). It is the first large-scale fully digital fabricated prototype, which is analogous to a building unit. Radiolaria was designed by using algorithmic rules based on the geometry of radiolari (micro organisms). The order of magnitude of these radiolari organisms is between a tenth and one-hundredth of a millimeter. They were used as an example for the morphological and static performance optimization of the unicellular structure that constitutes them. The close observation of nature led to the choice of the ALM process as the optimum construction technology. It allows depositing layers of material in an additive way only where indispensable, without waste, imitating the processes of formation of biological elements (Menges, A., 2012).

Cold extrusion machines are devices programmable to deposit superimposed layers of a viscous mix, often raw soil or cement-based. The mix can solidify quickly. The limitation of this technology is gravity. The physical outcome should be generated following the vertical axis. ALM technology allows processing building products through a wet process, simplifying site logistics by eliminating formworks for casting and long curing time of the material. An example of realization with cold extrusion was obtained in 2014 in the laboratories of the Institute of Advanced Architecture of Catalonia (IAAC) with the Pylos project. Researchers built raw soil-based wall modules, designed to withstand high compressive stresses (Dubor et al., 2018). The mixes suitable for extrusion, depending on the design ambitions, can be raw soil-based (Shamballa Village, by Wasproject),[14] plastic polymers (Mataerial, developed at IAAC),[15] or concrete (Yhnova, project carried out at the University of Nantes).[16] This technology, in particular, following circular business models, is targeted at reducing the consumption of resources and introducing recycled components into marketable products. It also offers the possibility of experimenting with the use of recycled materials such as, for example, construction site waste.

Among the processes that aroused the interest of the scientific community towards ALM in architecture, there is the above mentioned Contour Crafting project by Behrokh Khoshnevis, director of the Center for Rapid Automated Fabrication Technologies. The project highlights the operational methodology through which the layers become the fundamental geometric entities of the construction process. In Khoshnevis' vision, the buildings take shape within the printing area of the cartesian machine, which is scaled-up as well. This approach was taken as a reference by many companies doing research in the sector, primarily focusing on cold extrusion with materials such as clay, cement, plastic polymers, and geopolymers. Although the technology is mature enough for the production of vertical and inclined elements, an open challenge remains the realization of horizontal planes. New scenarios offered by the synergy between the digitalization of the building process and new paradigms of production of architectural products are opening. Designers should be aware of the new logic of intervention, innovative materials, and original expressive language. These elements will allow the overcoming two key concepts that have always characterized building design. On the one hand, the traditional concept of the three-dimensional representation of digital models, as simplification and abstraction of reality, is getting obsolete. The digital model, conceived as a physical representation, a simulation, carried out through software, suitable to study the behavior in certain situations, is overcome. The model becomes, instead, as a product of a creative-interpretative act, a contribution of knowledge about the building. It informs production and becomes matter itself. On the other hand, we see the surpassing of the concept of standardization, resulting from off-site production. The need to produce components off-site in an industrialized manner loses significance. The advantages offered by on-site production make it possible to go beyond the traditional logic of how materials get delivered to construction sites. At the same time, it remains necessary to guarantee the quality and performance standards, not to lose the quality of construction. Robotic manufacturing and 3D printing are innovative manufacturing technologies capable of expanding the range of design possibilities to materialize complex and informed morphologies. In this study context, it is necessary to understand the technologies and analyze the benefits they can bring in terms of environmental sustainability and product innovation.

11 Dshape company: https://d-shape.com/.

12 Shiro Studio: http://www.shiro-studio.com/.

13 Radiolaria project: http://www.shiro-studio.com/radiolaria.php, https://d-shape.com/portfolio-item/public/.

14 Shamballa VIllage, by Wasproject: https://www.3dwasp.com/viaggio-a-shamballa/.

15 Pylos Project at IAAC: https://iaac.net/project/pylos/.

16 Yhnova project at the University of Nantes: http://batiprint3d.fr/en/

3.3.1 Overview on precedent testing of clay-based Robotic Additive Manufacturing

The dissertation has a focus on practical application to support the arguments exposed. In order to perform speculative work on the digital recovery of Cultural Heritage, robotic technologies offer a great operational flexibility. Moreover, clay is used as a reference material. It has the potential to be versatile, economical, and sustainable for laboratory experiments. Finally, ALM is a challenging and complex technology that highlights many difficulties to be solved during the digital manufacturing process. The examples of robotic designs of clay-based forms are shown below. They represent a vaulable direction to formulate a hypothetical workflow and validate a proof of concept. The following section documents knowledge acquired in the analysis of experiments carried out by international research groups on robotic additive manufacturing (RAM).[17] Particular efforts were made to analyze laboratory tests that had defined the geometry of the toolpath as an element of complexity to solve. Tests that deployed cold extrusion with clay material were studied especially if used to demonstrate concept tests. Cold extrusion had specific merits as it is sustainable, low cost, and versatile. It was not a requirement that the selected projects relate to large-scale materials engineering at this point. The projects were also understood as satisfying only some of the constraints for the proposed experiment as it is easy to imagine the limits of the use of robots on-site, due to problems related to safety, transportation, and maintenance, none of which these projects are able to currently address.

Taking as a reference *Rob|Arch*, one of the most prestigious conferences in the field of robotic applications in architecture, it was possible to notice a refinement in the approach and in the methods of experimentation of robotic arms in relation to the use of clay. Laboratory tests presented and published in 2012[18] for scientific dissemination, for example, saw robots mainly used for the execution of subtractive procedures, surfacing or patterning of large-scale elements that were unique or assembled. With the Design Robotics project, facade elements[19] were designed by cutting clay sheets (Bechthold and King, 2012). With Robosculpt (Schwartz and Prasad, 2012), the researchers studied end-effectors able to chisel clay surfaces of objects in free forms. In 2014[20] the approach to surface and volumetric processing is deepened with the Objects of Rotation projects (Dickey et al., 2014) through the addition of a rotational axis in the sequences of material subtraction from the initial volume. With the Reusable Clay Mold experimentation (Schwartz and Prasad, 2012), instead, concept proofs were introduced for the realization of sustainable formworks free from geometric limits. The real turning point, however, is given by the case study Woven Clay (Friedman et al., 2014), performed by researchers at Harvard GSD. It was the first technical validation of the robot-extruder system - freeform toolpath, for the materialization of curvilinear print paths to form a system of interwoven

17 Robot Pottery's Golden Age: http://www.slate.com/features/drivingforces/ceramics/index.html?via=gd-pr-consent Clay Robotics: the future of architecture: https://www.theguardian.com/artanddesign/architecture-design-blog/ 2014/aug/08/clay-robotics-architecture-chilterns-farm.
18 Rob|Arch 2012 website: http://www.robarch2012.org/.
19 In 2012, the Building Bytes 3D printed bricks project by Brian Peters was published, for which a table-top 3D printer was used to extrude ceramic bricks into free assembled and statically performing forms. For more information see: https://www.dezeen.com/2012/10/31/building-bytes-3d-printed-bricks-brian-peters/.
20 Rob|Arch 2014 website: http://www.robarch2014.org/.

and overlapping splines, as an aesthetic language for a modular façade element. This experiment represented a prior guiding for numerous subsequent research activities that gave results such as Robotic Free Form Clay Formwork, presented in *Rob|Arch 2016*, or the Multi-axis 3D printing clay of 2018, briefly described below. The dissemination of these various research projects led to the creation of several subsequent prototypes from other research groups. These subsequent projects used robots not only to increase production efficiency, but to expand the possibilities offered by traditional design methods. The projects used performance as design inputs within a data-driven logic resulting in a generative iterative computational process (Figliola, 2017). The dissemination of the experimental results, year after year, has been fundamental to encourage the advancement of the state of the art of theoretical and technical knowledge in this field of study. Below is a brief description of significant case studies of robotic clay extrusion.

Woven clay

The Woven Clay[21] project was conducted in 2014 as an attempt to explore the application possibilities of large-scale cold extrusion technology layer-by-layer. For this reason an end-effector was designed (King et al., 2011) by the Design Robotics group at Harvard GSD - Graduate School of Design. The end-effector worked by mechanical means with a gear motor that drove a lead screw into a plunger that pushed the clay through a custom nozzle. A removable canister held the clay, which was loaded before each run. Through this system it was possible to define the suitable extrusion diameter and the density of the ceramic material in order to generate a pattern of intertwined lines on a double curved support surface, generated by subtraction with a numerical control machine. Numerous technical complexity factors have been studied, such as the adherence of the material on an inclined surface, the adjustment of the robot speed in relation to the extrusion speed, the operation of a customized volumetric extruder to make the material flow at a constant pressure through an output channel. The computational aspect was managed using the components for Rhinoceros Grasshopper and HAL. The forms produced by this procedure are unitary elements to be assembled to define a facade cladding in free forms.

Robotic free form clay formwork

The Robotic Free Form Clay Formwork experiment, carried out at the University of Sydney in 2016, represented an attempt at additive manufacturing in free forms using a six-axis industrial robot. The goal was to create sustainable clay formworks on the base in a mold made of milled wood. For this purpose the end-effector was defined by a progressive cavity pump with a stainless steel core. Drafting from a plastic reservoir connected by a flexible hose that fed the material into the pump,

21 Woven Clay process: https://vimeo.com/94076860. The project was published in several online platforms. For further information, see: 1) https://www.wired.com/2014/06/harvard-robot-whiz-invents-a-way-to-weave-build-facades-out-of-clay/ 2) https://3dclayprinting.com/woven-clay-by-jared-friedmand/. In 2018, the Cornell University develops the experimentation Digital Ceramics: Clay Tectonics, an exploration of robotic fabrications of traditional craft methods and materials. Clay weaving in one of the outcomes: https://aap.cornell.edu/student-work/clay-non-wovens.

and a hose attached to the robot (Dunn et al., 2016). The additive manufacturing process took place within the geometric limits of the milled cavity. The clay was then extruded on an inclined surface and it was necessary to verify its density and drying time so that it could solidify, remaining in position and maintaining adherence with the contact surface. For this purpose, an iteration of customized end-effectors was designed to optimize the relationship between robot kinematics and mechanical extrusion process. The design of the toolpath was performed using the software tool Kuka | Prc.

Informed ceramics: multi-axis 3D printing

In 2018 the University of Seoul refined the technical procedure of robotic extrusion of ceramic material on a doubly inclined curved surface (Dai et al., 2018). To achieve an optimal result,[22] the researchers made several iterations for the definition of the end-effector, especially given the need to store enough material to reduce refill operations.[23] The robot deposited porous clay on a freeform mold using the developed syringe-type clay extruder. The processed panel was designed with a diagrid pattern to secure structural stiffness after drying and kiln firing. Before making the final mold, 3D printing tests were carried out to understand the maximum inclination on which to perform extrusion operations based on the number of overlapping layers, before the material collapsed. The toolpath was designed to make the extruded clay bodies overlap and conjoin at nodal points. In-house Gerty and Robot Studio[24] plug-ins using Grasshopper were used to conduct accurate simulation of the robot behavior and create the toolpath. The customization of the process in this case also occurred at the software level. The papers published in these conference cycles[25] are useful for setting the operating methodology for the laboratory experiment for this research. In order to develop the specific skills to set up the tools and software for the experiment related to this thesis it was necessary to interview tool makers and experts in robotic manufacturing. Mark Meier[26] and Asa Peller[27] of Taubman College - University of Michigan and Jonathon Anderson[28] of Toronto's Ryerson School of Interior Design provided valuable input in the extruder and end-effector design phases.

22 B-at Lab at University of Seoul: http://b-at.kr/informedceramics.
23 Informed Ceramics process: https://vimeo.com/232737190. The project was exhibited at the 2017 Seoul Biennale: http://seoulbiennale.org/ko/exhibitions/live-projects/production-city/robotic-ceramics-in-architecture.
24 Robot Studio is a software developed by ABB Robotics: https://new.abb.com/products/robotics/robotstudio.
25 See also other cycles of international conferences aimed at spreading academic experiments in the field of advanced digital fabrication such as: - *Fabricate*, http://www.fabricate.org/, a biennial event organized by the Bartlett School of Architecture in London, https://www.ucl.ac.uk/bartlett/architecture/research/fabricate; - ACE Workshop, an annual event organized by the Ecole Centrale de Lille, especially focusing on additive manufacturing in the construction sector, https://ace-workshop.com/; - Fab Conference, annual meeting organized by the Fab Lab of Santiago, http://fab13.fabevent.org/conference/.
26 Mark Meier, lecture in architecture at UofM: https://taubmancollege.umich.edu/ faculty/directory/mark-meier.
27 Asa Peller, lecturer in architecture at UofM: https://taubmancollege.umich.edu/faculty/directory/asa-peller.
28 Jonathon Anderson, associate professor at Ryerson School of Interior Design (RSID): https://rsid.ryerson.ca/person/faculty/jonathon-anderson. Jonathon is the director at RSID of the FCAD - Digital Fabrication Lab: https://fablab.ryerson.ca/.

3.4 Robots: the assembly line applied for customized architecture

"The narrative of industrialization of construction is permeated by utopian concerns such as the desire to reconcile nature and technology, the project to free man of unnecessarily harsh work [Antoine Picon, 2014]

One of the phases of this research is the application of a robotic workflow in relation to a pre-existing geometry to manage automatic tools in the design and production process. For this purpose, it was essential to explore potential and critical issues arising from the application of new operating methodologies. Robotics is a decisive expression of the CAD/CAM relationship. It represents the immediacy between the mind and the built reality (Picon, 2014), which means between the design and production of the architectural project. Indeed, "geometry and algorithms can exist in the abstract, but to be of any practical significance, to become a design tool which can be used by designers, then these have to be encapsulated in an executable form" (Aish, 2013).

As all major handbooks in the field mention, such as *Robot Technology Fundamentals* (Keramas et al., 1998) or *The Robot: the life story of a technology* (Nocks, 2007), the field of robotics has its origins in science fiction. The term robot comes from an English translation of the Czechoslovakian word "robota" coined by the writer Karel Capek (1890-1938) for his 1921 play *RUR - Rossum's Universal Robots*. The modern technology of industrial robotics began at least forty years after. In Czech, robot means "boredom", "monotony", or "forced labor". It "alludes to slavery, forced labor, or even repetitive tasks as notably demanded by factory assembly lines" (Carpo and Lemerle eds., 2013). Therefore, in Capek's play, robots are depicted as humanoid slaves. Although Capek introduced the word "robot", Leonardo Da Vinci had the intuition to consider automatons as technological entities in 1495, and Charles Babbage had already envisioned, in 1832, a future where humans would never have to perform repetitive tasks. More specifically, the terms "robotics" was coined by Isaac Asimov in his science fiction story *Runaround*, first published in 1942 in the journal *Astounding Science-Fiction*. Asimov elaborated in his story the Three Fundamental Laws of Robotics as follow:

- a robot may not injure a human being or, through interaction, allow a human being to come to harm;
- a robot must obey the orders given it by human beings, except where such orders would conflict with the First Law;
- a robot must protect its own existence as long as such protection does not conflict with the First and Second Laws.

An interesting development is the addition of the Law Zero, written by Asimov himself in the book *Robots and Empire* of 1985, revolutionizing the previous Three Laws:

- a robot cannot harm humanity, nor can it allow humanity to be harmed because of its non-intervention.

This specification is particularly relevant, especially in technologically advanced communities where work possibilities for human-robot interaction have already been initiated. Simultaneously with the enunciation of the Zero Law, The Three Laws were taken over in 1985 by Shimon Nof. In the publication *Handbook of Industrial Robotics*, he explains that "when Isaac Asimov wrote his Three Laws of Robotics in 1949, his purpose was to guide robots in their attitude towards humans. At present, our society is more concerned with our own attitude toward robots". For this reason, he formulates The Three Laws of Robotic Application:

- robots must continue to replace people on dangerous jobs (this benefits all);
- robots must continue to replace people on jobs people do not want to do (this also benefits all);
- robots should replace people on jobs robots do more economically (this will initially disadvantage many, but inevitably will benefit all as in the first and second law).

These laws emerge from an awareness of the enormous potential that robots have in manufacturing. These advantages are both economic and social, i.e. they allow the reduction of production costs and the protection of workers from difficult or dangerous processes. Moving from sci-fi to reality, the first industrial robot was tested within the automobile sector. It was based on the patent *Programmed Article Transfer* (programmable automatic machine) of 1961, by the American engineers George Devol and Joseph Engelberger for the company Unimation. Contrarily to Capek's humanoids and Asimov's artificial agents, the first automatic machine was neither a robot soldier nor a spacewalker. The development of the prototype culminated with Unimate#001,[29] a hydraulic manipulator arm that was installed in a General Motors factory in New Jersey to do welding and extracting die-castings. Unimate could repeat arbitrary sequences of motions. The purpose of its use was to replace man in dangerous and extremely repetitive tasks that characterize the 4D (dangerous, dull, dirty, and dumb) and 4H (hot, heavy, hazardous, and humble) jobs. Compared to other manufacturing technologies, the robot is not considered a utensil, as it was created to replace man. More advanced computer-controlled, sensor-driven electric arms were developed in the late 1960's and 1970's at MIT and Stanford University, where computer-controlled all-electric robots were developed. Examples of this type are the IRB-6 robot from ESEA, the Kuka Famulus, an anthropomorphic robot with six axes of freedom. A further example is the PUMA (Programmable Universal Machine for Assembly), which was used in 1978 for the assembly of automotive components. Since the 1990s, small electric arms or service robots have also become widespread in the fields of medicine and advanced biology.

Today, the main manufacturers of robots are Kuka, ABB, and Fanuc. Robots are iconic tools of The Fourth Industrial Revolution and are evolving in parallel to IT disciplines. The official definition of an industrial robot is provided by the *Robotics Industries Association* (RIA): "an industrial robot is reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or special devices through variable programmed motions for the performance of a variety of tasks".[30] An industrial robot has also been described by the *International Standards Organization* (ISO) as follows: "a machine formed by a mechanism including several degrees of freedom, often having the appearance of one or several arms ending in wrist capable of holding a tool, a workpiece, or an inspection device. In particular, its central control unit must use a memorizing device and it may sometimes use sensing or adaptation

29 Unimate robot: https://www.britannica.com/technology/Unimate.

30 RIA: https://www.robotics.org/.

appliances to take into account environment and circumstances. These multipurpose machines are generally designed to carry out a repetitive function and can be adapted to other operations".[31] In other words, "the primary purpose of the robot as a machine is controlled motion: if it does not move, it is not a robot" (Keramas et al., 1998). For the time being, the human mind puts them in motion (Picon, 2014). Moreover, robots are mechanical devices that assist industrial automation. The concept of automation is related to technology. In an industrial context, automation can be defined as a technology that is concerned with the use of mechanical, electrical, and computer-based systems to control production processes. Examples include numerically control machine tools, mechanized assembly machines, and robots.

Robots are available in a range of shapes, sizes, speeds, and load capacities. The motion characteristics of robots vary, depending upon their mechanical design. Five common anatomies are associable to commercialized robots:

1. **Rectangular (or cartesian);**
2. **Cylindrical (or post-type);**
3. **Spherical (or polar);**
4. **Jointed-arm (articulated or revolute);**
5. **SCARA (Selective Compliance Assembly Robot Arm).**

More closely, the jointed-arm has three rotary motions to reach any point in space. The design is similar to a human arm. Jointed-arm robots are generic machines that emulate the craftspeople's arm (Bonwetsch et al, 2010). This type of robot can move at high speeds in various directions and has a greater variety of angles of approach to a given point. Usually, based on the number of axes, joints are called: A1, A2, A3, A4, A5, and A6. They allow the robot to perform kinematics and interact with the surrounding three-dimensional environment. As James Keramas explains, "a robot can become a production machine only if a tool or device has been attached to its mechanical arm by means of the tool-mounting plate". This device is called end-effector. It defined the material machining process. The tool centre point (TCP) is the origin of the coordinate system or the point of action of the tool attached to the robot arm. Depending on the type of operation, conventional end-effectors are equipped with various devices and tool attachments: grippers, electromagnets, adhesive fingers for materials handling, spray gun for painting, drills, nut drivers, special devices for assembly, dial indicators (measuring instruments), and extruders. Through the integration of sensors,[32] robots expand their capabilities. Robotic activity is elevated to a sophistication other than simple execution. Nevertheless, robots don't care about what they are doing. It's up to the human professionals to use robotics in a responsible way by elaborating post-Fordist successful models, relieving workers from painful tasks, and knowing that desperate automation is not a successful move. It will take at least 15 years of research before robots will be able to build other robots. Before then, robots can be integrated into existing workflows. The approaches for the use of robotics always remain versatility of use, adaptability, flexibility, precision, and repeatability of execution.

31 Robots and robotic devices - vocabulary: ISO 8373:2012.

32 Automation, feedback control: https://www.britannica.com/technology/automation/Feedback-controls.

3.5 International academic research on the development of construction robotics

"The various attempts to industrialize building activity throughout the 20th century were intimately related to a grand narrative regarding the necessity to adapt architecture to the age of the machine [Antoine Picon]

In this section, it is intended to briefly outline the most relevant international research on robotics in architecture. The use of robotic approaches for Cultural Heritage is not widespread. However, the investigation of the leading university research centers dealing with automation in the construction sector is useful to examine the potential and TRL of the technology, in its different models of application. The focus of this analysis is on experiments that investigate the feasibility of on-site robotics and the scale-up of workflows from design to architecture.

ETH Zurich - Chair of Architecture and Digital Fabrication

The Swiss Federal Institute of Technology in Zurich, Chair of Architecture and Digital Fabrication, has been an international reference in the field of digital architecture since 2000. Twenty years ago, Fabio Gramazio and Matthias Kohler founded the research center Gramazio&Kohler Research.[33] Their work led to the opening of the world's first robotic manufacturing laboratory in academia. It operates in close collaboration with the manufacturing industry. Among the courses offered by the department of architecture, the MAS ETH DFAB stands.[34] It is a one-year full-time Master of Advanced Studies in Architecture and Digital Fabrication. It includes the teaching of design and digital fabrication methods and technologies for large-scale applications in architecture and building design. This approach is a distinguishing feature of Gramazio and Kohler's work. Their efforts have surpassed the use of robots in higher-ed for the development of scale models. Conversely, the design purpose of the experimental outputs is the creation of 1:1 scale prototypes, to show the limits and potential of innovative digital workflows. These workflows do not focus on a single aspect, but integrate software development, testing of new materials, and custom programming of robots through work interfaces that are familiar to architects. The quality of Gramazio and Kohler's research led to the creation of the NCCR - National Center of Competence in Research. It is funded by numerous Swiss national programs, such as the SNSF - Swiss National Science Foundation, and the SDSC - Swiss Data Science Center. The ETH's work has the authority to represent a vanguard for other universities and to guide the technical and theoretical approach on an international scale. Both Gramazio and Kohler are authors of numerous publications, including *The Robotic Touch: How Robots Change Architecture*, where the concepts of digital materiality, algorithmic thinking, and large-scale robotics are explored (Kohler et al., 2014). The book is a review of their projects. The key themes that have been studied over the years are: the feedback loop strategy in robotics, parametric design and digital prefabrication, on-site robotics, innovative architectural production, and multi-robotic collaboration. The first iconic achievement was the construction of the facade of the Gantenbein Vineyard in 2006,[35] distinguished by its design complexity, characterized by the quality of the result guaranteed by robotic operations. The most recent disruptive example is the construction of the DFAB House,[36] a full-scale architectural system entirely executed through digital fabrication and, in particular, ALM and on-site robotics. In this case, the robots were programmed to perform multiple tasks and update the software platforms of the construction advances in real-time. The most recent research projects are currently breaking down the frontiers in the use of human-machine collaboration[37] and augmented reality by combining human knowledge with decision-making processes of automated systems.

33 Gramazio & Kohler Research: https://gramaziokohler.arch.ethz.ch/.

34 MAS ETH DFAB: https://www.masdfab.com/.

IAAC Barcelona - Institute of Advanced Architecture

The Institute of Advanced Architecture of Catalonia is an experimental research center founded in the 2000's. Like other institutions dealing with digital fabrication and advanced technological research, the IAAC's educational offer is addressed mainly to graduate students. Among the specialization programs, the Master in Robotics and Advanced Construction pursues the goal of defining design workflows that culminate in the customized robotic production of construction units on an architectural scale. There are numerous projects developed at IAAC that have been taken as a reference at the international level. Many of these are focused on additive manufacturing, led by the expertise of professors like Areti Markopoulou and Alexandre Dubor. The first example that is worthy of mention is Pylos,[38] developed in 2014. The project was conducted by the researcher Sofoklis Giannakopoulos, under the supervision, among others, of professors Markopoulou and Dubor and the support of the ALM expert Enrico Dini (Dshape). It explored the use of an extruder installed on a robot for the construction of technological units on an architectural scale using a natural clay-based material. This process allowed the production of columns with a customized geometry over two meters high through precision and quality of surface treatment. The development of this project is represented by the recent collaboration of IAAC with Wasp company for the realization of a load-bearing earthen structure through ALM. From the production of customized columns, researchers moved to the creation of an architectural sub-system, developing the concept of digital tectonics in a concrete way. A further example is the experimentation Mataerial.[39] It is an additive robotic production methodology. It allows to create extrusions in three-dimensional space without the need for additional support structures. Conventional additive manufacturing methods, in particular desk-3D printing, are influenced by both gravity and the printing environment. In addition to additive robotic production workflows, IAAC also deals with innovation in the building process. The research Minibuilders[40] has deepened the coexistence of a single-task robot swarm on-site, trying to bring back to the present day the automation that had been experimented since the 1970's in Europe and Japan.

35 The Programmed Wall Project for the Gantenbein Vineyard: https://gramaziokohler.arch.ethz.ch/web/e/lehre/81.html. Also available at: http://www.gramaziokohler.com/web/d/bauten/52.html; https://vimeo.com/69252842.

36 DFAB House: http://www.dfab.ch/tag/dfab-house/; https://vimeo.com/223502304.

37 Human-Machine collaboration project: https://gramaziokohler.arch.ethz.ch/web/e/forschung/372.html.

38 Pylos project at IAAC: https://iaac.net/project/pylos/; https://vimeo.com/140196612.

39 Mataerial project at IAAC: http://www.mataerial.com/; https://vimeo.com/55657102.

40 Minibuilders project at IAAC: https://iaac.net/project/minibuilders/.

UCL London - The Bartlett School of Architecture

The research carried out at Bartlett in London is mostly the result of the work done in the Design for Manufacture MArch program. In this post-graduation course, students are exposed to the issues that characterize the Fourth Industrial Revolution, i.e., the transformations in manufacturing involving digital design, computational workflows, and automation.[41] In 2011, The Bartlett promoted and hosted *Fabricate*, one of the first conferences in the world that featured robotic manufacturing in architecture. This event allowed the scientific community to discuss the progress of academic research in advanced digital fabrication and automation. The success of *Fabricate*, as a statement of the state of knowledge in the higher education, gave the momentum for the creation in the following year of the community *Association for Robots in Architecture - Rob|Arch*, by Johannes Braumann. The purpose of the community is to make robotic arms accessible to the creative industry. Bob Sheil directs the School of Architecture at Bartlett. He's also the author of the book *Manufacturing the Bespoke*, a collection of international projects that narrate the shift to the use of automation in architecture through the digital revolutions that occurred after the 1980's. Bartlett is also known as a center for the theorization of architecture. Mario Carpo, professor of History of Digital Architecture, coined the expression Second Digital Turn. This historical moment compensates for the lack of material dimension that occurred during the first digital era of the 1990's. Moreover, professors Mollie Claypool, Manuel Jimenez Garcia, Gilles Retsin, and Vicebte Soler have recently published *Robotic Building - Architecture in the Age of Automation*, a book that gives voice to experts in the field such as Antoine Picon, Greg Lynn, and Jan Knippers. Finally, to mention another one, Marjan Colletti, using an approach similar to Benjamin Dillenburger's work[42] at the University of Toronto, investigates the formal effects of digital fabrication and the contemporary rediscovery of design ornament. The Bartlett is an excellent example of an Institution that operates with technical and theoretical scientific rigor.

University of Michigan - Taubman College of Architecture and Urban Planning

The Taubman College at the University of Michigan has one of the largest Fabrication and Robotics Labs in the world, equipped with the most advanced robotic systems. The director is Wes McGee, who co-authored with Monica Ponce de Leon the publication *Rob|Arch 2014*. The book was the result of work collected during the *Robotic Fabrication in Architecture, Art, and Design* conference, which was followed by a series of design workshops on the subject. Wes McGee is also co-founder, together with Brandon Clifford and Jo Lobdell of Matter Design studio,[43] a practice that works exclusively by shaping matter with digital tools. Their project Cyclopean Cannibalism of 2017, published in *Robotic Building - Architecture in the Age of Automation*, explores the concept of digital vernacular by customizing the texture of a stone wall whose discreet elements derive from the Inca tradition of

41 Design for Manufacture MArch program: https://www.ucl.ac.uk/bartlett/architecture/programmes/postgraduate/march-design-for-manufacture.

42 Benjamin Dillenburger - Numerical Material: https://benjamin-dillenburger.com/.

43 Matter Design Studio: http://www.matterdesignstudio.com/.

assembling Mattebuilding elements. A 2018 project conceived by Wes McGee, Tsz Yan Ng, and Asa Peller explored an innovative robotic felting technique for the production of functionally optimized and design-advanced architectural cladding elements. As explained by the researchers, in the project Hard+Soft - Robotic Needle Felting For Nonwoven Textiles "through a digital workflow, formal and material properties are computationally informed and can be varied continuously. This capacity for designed variation opens a wide range of potentials for architectural design and applications".[44] On the theoretical level, a key professor in this Institution is Malcolm McCullough, who, through the publication *Abstracting craft: The practiced digital hand*, is a spokesman for the concept of digital craftsmanship.

University of Stuttgart - ICD Institute for Computational Design and Construction

The Computational Construction Laboratory and Robotic Fabrication Laboratory of the ICD Stuttgart are focused on robotic production methods to support biomimetic architectural languages, through the study of biological phenomena and their transfer into building design (Menges et al., 2013). The director is professor Achim Menges. He contributed to disseminate the research developments conducted at the ICD, through the development of the Research Pavilions realized in collaboration with the ITKE - Institute of Building Structure and Structural Design. The experiments concerned the development of complex 1:1 scale morphologies generated both through traditional materials, such as wood, and high-engineered materials, such as carbon fibers or smart materials (Addington, 2005) that support the formal generation of the outcomes through their inherent characteristics. The design complexity derived from the introduction of biological principles in the design process, defined by Menges as morphogenetic design, is managed with robots. Robotic manufacturing is not subject to the geometrical and morphological restrictions imposed by industrial-derived production processes leading to mass production of the same construction element (Figliola, 2017). The Research Pavilions of 2014 and 2016 allowed exploring complex robotic manufacturing workflows. Both projects are the result of design optimization of the structural tectonic and the minimization of the use of materials. The pavilions realized in 2019, respectively, the BUGA Wood Pavilion and the BUGA Fiber Pavilion,[45] are ambitious manifestos of the realization of morphogenetic architectures through robotic fabrication. The description of the BUGA Fiber Pavilion for example states that the aim of the project is to "transfer this biological principle of load-adapted and thus highly differentiated fibre composite systems into architecture. Man made composites, such as the glass- or carbon-fibre-reinforced plastics that were used for this building, are ideally suited for such an approach because they share their fundamental characteristics with natural composites". The latter, together with the Urbach Tower project[46] are the spokesmen of a growing awareness of the management of large-scale robotic processes.

44 Hard+Soft - Robotic Needle Felting For Nonwoven Textiles: https://taubmancollege.umich.edu/research/research-through-making/2018/hard-soft-robotic-needle-felting-nonwoven-textiles.

45 BUGA Wood Pavilion: https://www.icd.uni-stuttgart.de/projects/buga-wood-pavilion-2019/. BUGA Fiber Pavilion: https://www.icd.uni-stuttgart.de/projects/buga-fiber-pavilion/.

46 Urbach Tower: https://www.icd.uni-stuttgart.de/projects/remstal-gartenschau-2019-urbach-turm/.

3.6 The role of higher-education: speculative physical models created through a robotic process

"Coding is the lingua franca of the digital world, everyone should be conversant in it [Joseph Aoun, 2018]

New opportunities exist to imagine the architectural model in a digital era. Rather than view the physical and digital as oppositional, both model types possess qualities of operation, performance, and mediation. This section discusses the speculative physical model as the driving motivation for a three-credit elective seminar - Introduction to Robotic Fabrication. The undergraduate/graduate course did so with students without any previous robotic exposure. Speculative architectural models confront material, production, sequence, and gravity. Models are surrogates, as all forms of design must confront translating ideas to reality. Typically, designers specify, while others build those designs. Designers' models translate issues of scale and production. The course operates in opposition to digital fabrication courses where furniture-scale prototypes result. Speculative scale models utilized the robot as a mediator in a speculative construction process. By building models, students understood their work to be at a large-scale which would then require robots to be construction tools.

Contemporary design takes place within the framework of a global change that simultaneously affects the manufacturing, education, and research sectors known as the Fourth Industrial Revolution (Schwab, 2017). The Fourth Industrial Revolution is based on the spread of cyber-physical machines or systems interconnected through the internet of things that allow automation of the tasks necessary to carry out complex processes. In other words, this technological era is represented by the diffusion of production tools that have an impact on the professional skills needed to govern them. The computer democratized as part of the digital revolution, is not only a design tool, but a mediator that translates digital models into programming languages readable by 3D printers, numerical control machines, laser cutters, and robots (Picon, 2010). The consequence in architecture lies in the openness to new design languages that encourage the development of innovative construction techniques for the rapid production of technological elements, disconnected from the impositions of prefabrication. In architecture, the compression between design and construction has been theorized by Mario Carpo as Digital Turn, which develops in two consequential phases. With the first Digital Turn, new possibilities opened up through the computational thinking in design processes (Carpo, 2013). With the Second Digital Turn, more in line with the shift dictated by the Fourth Industrial Revolution, robotic proliferation leads to a synthesis of algorithmic and parametric design informed by advanced forms of making. Robots can process and cut material while also assembling discrete, heterogeneous parts. Parametric thinking allows designers to understand projects as a set of operations, and the robot can support this type of production where parameters result in accurate iterations controlled by robotic making.

The robotics course presented in this paper, which has as its output the definition of architectural scale models, is based on the realization that the current system of higher education is conditioned by dynamics that disadvantage students' cognitive opportunities. In the academic field, within the design generation workflows, the cost of making models progressively goes up, while on the contrary the cost of making digital models goes down. This trend causes students to move away from the cognitive and tactile experience of making physical models. From this, a loss of physical modeling takes place, which follows a loss of kinesthetic knowledge and rigor in the design process. The possibilities dictated by the digital era encourage morphological explorations through 3D printing. However, 3D printing exists more as direct output biasing geometry over performance. While an essential tool, there is an inherent lack of materiality in 3D printing.

The realization of analog physical models has several advantages. First, they are configured as a medium to make the process explicit and to make the understanding of the project accessible to both the student and the educator (Voulgarelis & Morkel, 2010). Moreover, maquettes represent a graphic form defined by a material dimension where surfaces are informed by a tactile knowledge (Ingold, 2013). The knowledge gained by making can only occur through doing. Marty Neumeier in the book *Meta Skills, Five Talents for the Robotic Age* articulates this with, "500 years after Renaissance, academic education in the West has been successful in separating the hand from the brain. We've decided that making things is less valuable than knowing things, and therefore making has a less place in the classroom. This is not only wrong, but it denies the very evolutionary advantage of being human". Neumeier also adds that to cultivate the necessary skills in the contemporary world, "making is rejoined with knowing" (Neumeier, 2012). This is fundamental especially in the discipline of architecture, which in the Vitruvian definition results from the fusion of theory and practice. In his *Ten Books on Architecture*, Vitruvius advocates on the need for architects to possess theoretical and practical knowledge, to combine manual skills with deep scholarship. In particular, practice is described as "the frequent and continued contemplation of the mode of executing any given work, or of the mere operation of the hands, for the conversion of the material in the best and readiest way" (Pollio, 1914).

In the construction tradition, craftspeople are those professional figures who embody the synthesis between theoretical knowledge and practical experience, manifesting the approach learning by doing and thinking through making, "rather than acquiring theoretical precepts for subsequent application in practice" (Ingold, 2013). An interpretation of the concept of learning by doing is inherent in the theorization of Il Discorso Mentale, the mental conversation, of which Leonardo Da Vinci speaks in reference to the creative process for the creation of works of art such as paintings: "to Leonardo, an artist didn't learn to paint. He painted to learn" (Neumeier, 2012).

Therefore, through the teaching activity, the course emphasizes making as an attitude to study material and focus attention to the detail. The course attempts to recover the sense of materiality which is lost with simple BIM models and additive rapid prototyping. The production of architectural models is a good opportunity to explore the cultural implications and the transposition of the skills of future operators of the Fourth Industrial Revolution. In contrast to the simple output afforded by 3D printing, robots operate as mediators building the students' translational skills. By exploring the robotic possibilities to make scale models, it is possible to refine the skills of digital fabrication while exploring matter, which informs the programming of design algorithms in an iterative way.

3.6.1 Learning through making scale models

This course balanced theoretical and instrumental aspects through readings that introduced topics, demonstrations of software, and hands-on sessions for introducing robotic / student interactions and protocols. This approach highlighted that production is no longer solely the last step of the design process. The technical knowledge taught was used to understand the potential and operational limits of the robot, from workcell to the limit angles of the axis kinematics, in order to approach the design process accordingly. In parallel, theoretical knowledge laid the foundations to open a dialogue on the speculative value of architectural models.

The concept of scale model as machine (Smith, 2007) was introduced to explain the evocative quality of architectural models, not only as objects of study but as an expression of a deep value system. The first example discussed was Gaudi's approach to the creation of scale models. Although the architect worked at the turn of the nineteenth and twentieth centuries, his "reference standards" were those of the Middle Ages, a period in which making architecture was guided by the master-builder, a craftsperson who, without the need to produce drawings, directed the day-to-day construction. In the same way, Gaudì in his professional life did not make any written notation to represent his projects. For Gaudì the realization of scale models served not only to explain to the craftspeople his complex geometric ideas, but above all to recall the moral and religious social order of the past, as an example to be pursued. Among the methods used by the architect to understand the systems of forces in the load-bearing structures, there is the process of hanging chains upside down above a mirror. In this way he created real "machines" to explore nature and to understand the truth of invisible reality, or in other words, God. The search for the unknown also belongs to Louis Kahn's work. As Albert Smith explains in his book *Architectural Model as Machine*, in developing his design processes Kahn discovered that "the scale model machine presents not only the possibility of seeing and defining the narrative of the myth, but also seeing its failing" (Smith, 2007). It is part of this narrative to find out what the future appearance of a building will look like or how the scale model will contribute to the advancement of design towards construction, whether by suggesting a different approach to materials or changing proportional ratios. Since in Kahn's poetics, as in Gaudi's, there was a profound spirituality underlying it, he saw in the order that springs from architecture, an allegory of the Universe unifying all things. In both instances the architect saw great intellectual value in the creation of physical models.

From an educational point of view, we tried to convey the fact that an architectural model is a prototype that serves to convey an idea and transform it during the design process. Like a prop in the theatrical lexicon, the scale model is an object that serves to build a concept and make it explicit through its materialization. Students were also exposed to the idea that direct experience has cognitive benefits on learning. Just as Leonardo Da Vinci used painting as a means of knowledge, the architect can take the same path through the creation of study models. This knowledge building activity through direct tactile experience, through the medium of the hand touching material, is human learning and "will proceed without respect to any prediction of normative measures of intelligence" (Wilson, 1999). Paraphrasing Frank Wilson's words in The Hand: How Its Use Shapes the Brain, Language, and Human Culture, the hand that through external interactions trains the brain to understand them. In material exploration, "both the hand and the eye develop as sense organs through practice, which means that the brain teaches itself to synthesize visual and tactile perceptions by making the hand and eye learn to work together" (Wilson, 1999).

A physical model is an important cognitive part of the design process. It represents the connection point between thought and action, between tactile experience and the brain. In course, the robot exists as the translator between mind, digital conceptualization, and the material world. The designer's work space extends, as does the cognitive space. The use of industrial robots and design software allows a mutual communication between the parts and does not render the robot as simple executor. Moreover, the use of robots introduces us to a new process model in which a new aesthetics is inherent, both from the point of view of the possible geometrical results and of the speculative value related to them.

3.6.2 Teaching methodology of the digital (robo)fabrication class

A recent article "8 Things Every School Must Do To Prepare For The Fourth Industrial Revolution" published in *Forbes*, presents a lucid analysis of the educational offer that Higher Education should offer to make future professionals more responsive to the quickly evolving dynamics of the market. On the basis of future trends that will occur in the world of work, it will be necessary to emphasize, alongside humanities, the STEMS (science, technology, engineering, and mathematics) disciplines, as together with the critical thinking "there's no doubt every worker in the future will need some tech skills."[47]

A further point that is touched upon is the updating of teaching methods and themes.[48] The rapid changes in technology make traditional models obsolete, which require a large part of learning to take place by the end of university graduation. The acquisition of skills is driven by the ability to use the tools that require more than basic knowledge or the simple ability to follow instructions. These tools, as summarized by Darrell West in The Future of Work, fall within the macro-categories of automation, robotics, AI, machine learning, and IoT (West, 2018). They are the key to updating higher education through a non-static approach, so that the university education offer does not prepare for the future professionals that "we needed 50 years ago".[49]

By adopting this innovative drive, LTU - CoAD has defined the prerequisites for teaching an introductory course in robotic digital fabrication. The course is taught during one semester and is offered to a

47 The Future of Jobs Report 2018, by *The World Economic Forum*. In the introduction, the executive chairman Klaus Schwab states: "A particular focus of this new edition of the report is on arriving at a better understanding of the potential of new technologies, including automation and algorithms, to create new high-quality jobs and vastly improve the job quality and productivity of the existing work of human employees."

48 "8 Things Every School Must Do To Prepare For The 4th Industrial Revolution" in *Forbes*. Article by Bernard Marr, published on May 22nd, 2019.

49 "Andrew McAfee: The Second Machine Age Is Approaching. Here's How We Can Prepare", in *Huffpost*. Article by Dawn Nakagawa, published on February 24th, 2015.

small group of undergrad and grad students, with no prior exposure on the topic. The students used a Kuka Kr6 six-axis industrial Kuka robot, previously used in an automotive industry production chain and then absorbed by the university, which benefited from a lower investment than the purchase of a new tool just released on the market.

The use of "retired robots", or down cycled, or used, is currently a growing trend. Teaching and academic research are part of one of the areas in which it is possible to use retired robots in the post factory years, after the assembly line. The Economist's 2014 special report "Immigrants from the future" mentions the startup Bot and Dolly, later acquired by Google, which used industrial robots in new settings like that for art projects and the film industry. The robot-afterlife is a condition that is generated when manufacturing industries upgrade their production lines with more competitive and advanced instrumentation. However, robots can operate for many years after they are displaced from assembly lines, making them affordable to subsequent customers, who usually make targeted and less intensive use of them. These sectors do not have the capital purchasing power of the industries that originally purchased the robots. The reduced cost of used robots (Keramas, 1998) defines in parallel an exponential growth of technical and operational knowledge in the automation sector. In the case described in this paragraph, necessary expertise for the Fourth Industrial Revolution can be achieved through university arts education.

In the digital (robo)fabrication class, the teaching approach has been to consider the robot as a mediator to translate ideas into reality. Through robotic fabrication it is possible to transfer digital information into materiality through an instant connection between digital three-dimensional models and physical space. The course led students through a series of assignments that started with basic robotic programming, with various exercises along the way, to the culmination where the robot hotwire cut precision formwork for a series of plaster models. The flexibility allowed for the use of a single robotic process given different tools to perform additive, subtractive, hybrid, and assembly processes. Different actuators or end-effectors can be installed on the robot head to perform different tasks. This property makes the robot flexible and adaptable to different functions, with the possibility of making numerous iterations with increases in complexity and operational solutions for optimization. The digital interface visualizes the robot and its movements to detect and correct errors before execution in the physical world. Kuka|Prc is widespread in the academic world for programming Kuka robots because of the popularity and student familiarity with Rhino. Kuku|Prc's diffusion in academia is the result of its effectiveness of an online community active on the development of the theme, through which access to knowledge is reverberated to the non-experts.

The intense connectivity between design software and robotic output creates an instantaneous workflow. Designers are able to continue designing right up to the point they export robotic code for the production process. The design also goes beyond the limits of geometry and includes a schedule of new design parameters. In the context of the course, students limited themselves to the creation of speculative models, but the methodology is understood to be scalable and in so doing, challenging traditional design approaches. Through robotic digital fabrication you exit the sheet in order to make stuff, not only drawings of stuff (Gramazio et al., 2017).

3.6.3 New scenarios in construction and need for advanced skills

In the design and construction scenario that lies ahead, the master-builder / designer will take care of the entire production chain. This professional (or team of professionals) will need to be able to summarize the complexity of the workflows of The Fourth Industrial Revolution with respect to the logic that governs the agreed upon manufacturing processes. Experiments that investigate issues related to the synthesis of computation and digital fabrication as elements capable of triggering innovation point to an area of study increasingly oriented towards architecture / construction practice that involve industrial processes and academic training. Through this class, students had the opportunity to understand the value of knowing the difference between upstream and downstream processes. The upstream process includes design, i.e. the early-stage phase where the morphological decisions are set and the design strategy defined. In the future of construction, the downstream phases will be digitally connected and inevitably include tools such as robots. The downstream design process is informed by production methods, enriching the creative phase with data through the knowledge of tools that allow upstream cognitive integration. In this context, the algorithmic language is the link between the different phases of the workflow from design to construction.

In the class, a loose analogy between robots and contractors emerged and if one could explain intentions and constraints to a robot,[50] an emerging designer must be able to describe their intentions and instructions to a contractor or manufacturer. Architects can use digital technology to better understand downstream production processes. As a result, technical complexity can be handled early in the design process to make better informed decisions and achieve better operations. Students learned physical aspects of prototyping, with the aim of bringing digital fabrication back to a material dimension, combining architectural design and production process design in a hybrid workflow. The same workspace in which the robot operates is hybrid, as it is the means of a continuous exchange of information between real and digital and vice versa. The course focused on process analysis and cultural implications. Since it was an introductory course to robotic digital fabrication, students did not have to deal with design aspects such as functional program, occupancy, static operation, or placement on a project site. The work focused on the design goal phase, free from the rules that professional determinism imposes. Students practiced working out formal concepts and thinking about the tools that were used to produce them. Borrowing the words of Louis Kahn, 'form has nothing to do with circumstantial conditions' (Kahn, 2003). As a result, students were able to start building their own "reference standards" in anticipation of becoming the next professionals in architecture at the Fourth Industrial Revolution, with the socio-cultural consequences that it entails. Mediating design and material became the designer's key skills to utilize speculative models based on the new forms of digital models that define an emerging relationship between designer and tools.

50 The Construction Industry Needs a Robot Revolution in *Wired*: https://www.wired.com/story/the-construction-industry-needs-a-robot-revolution/

Fig. 3.8 The end-effector designed and fabricated during the Introduction to Digital (robo)Fabrication class. The students designed and fabricated them through 3D printing. Each actuator is customized to execute a specific task and therefore deliver the different class assignments.

Fig. 3.9 The grad and undergrad students of the Introduction to Digital (robo)Fabrication class, divided into three groups. Top left: Irene Missler, Eunpyeong Kim, Trent James, and Matthew Weyhmiller. Bottom left: Michael Zonca, Zakia Hunt, Francisco Landeros, and Aaron Wrubel. Right: Nathan Ickes and Jacob Croop.

AxisLogic

//Project001 - AxisLogic//

The intent of the Assignment 001 is to introduce the logic of a machine based on rotational, as opposed to linear axes, from the relative safety of your own computer. This assignment also verifies the installation of a working copy of Rhino, Grasshopper, and KUKA|prc.

//Low Level Skill Acquisition//

Project001 asks you to use sliders that control the position of each of the robot's individual rotational axes. You should maneuver the end of the robot to predefined locations in 3D space (included in the rhino file). You are also asked to find and define a point and orientation within the robot's work envelope that is unreachable due to axis limitations.

//Higher Level Skill Acquisition//

While you work, consider the difficulties you have making linear movements. Also, consider the complex combination of axes to do what should be a simple task. KUKA|prc allows you to simulate the robot's movement and position before you have to do anything in physical space.

//Feedback on AxisLogic assignment//

The most effective entry level mode to program a robot is to combine 3D modeling with custom made plugins to control machine operations through a digital interface. In this case Rhinoceros and Grasshopper have been implemented with Kuka|Prc, an add-on that converts geometry into robot-readable lines of code. An efficient workflow to program the robot kinematics consists in drawing the machine-path, or toolpath, in three-dimensional space. This, within the limits of the workcell, is the maximum extension that the axes can reach. The toolpath is then broken down into target points described through polar coordinates that constitute the instructions to be given to the robot, importing the file into its operating system. Through this assignment, the students were exposed to the logics the guide the robo-programming. In doing so, they had to understand the coordinate systems (world, base, or tool),[1] which may vary based on the point taken as origin. The coordinates are the instructions to be given to the robot, to execute a kinematics. The instructions are structured in rotations that every axis should do to reach a pre-determined target point.

1 Training on robot coordinate systems and kinematics available at: https://academy.universal-robots.com/.

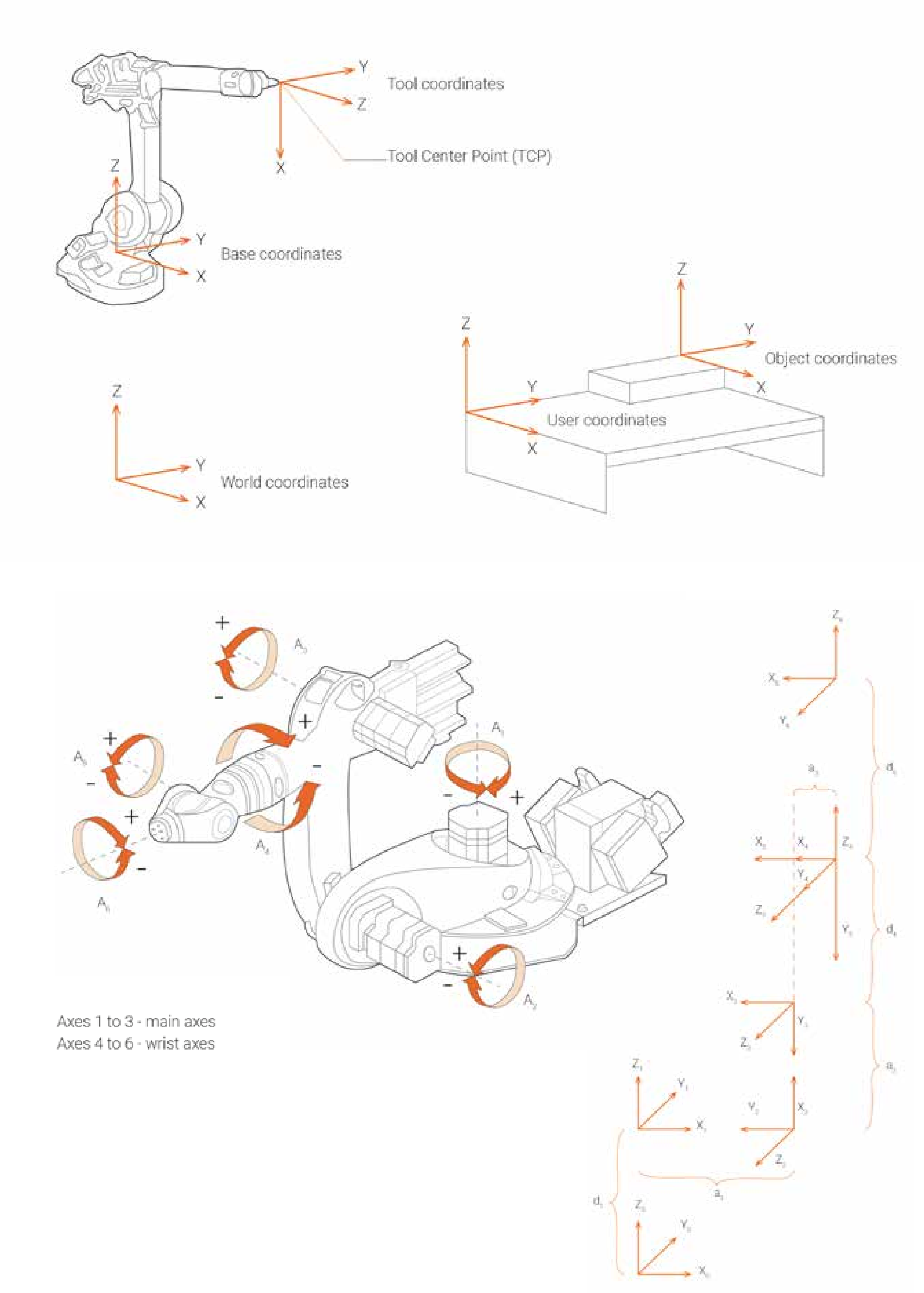


Fig. 3.10 Coordinate systems (world, base, tool, user, and object) and possible rotations (+/-) of a 6-axis robot.

aMAZEing

//Project002 - aMAZEing//

Building on the virtual experiment you did in Project001, this assignment puts you in contact with the robot in physical space. You will manually jog the robot in axis mode to move the end-effector from start to finish within the designated path. Then using a programmed path you will move the robot along a simple path as defined by the computer.

//Low Level Skill Acquisition//

Project002 asks you to enable and jog the robot to do simple linear moves. It then asks you to output and run your own simple robot code. Subdivide a toolpath by points and generate fixed orientation LIN moves for the robot.

//Higher Level Skill Acquisition//

While you work, consider the difficulties you have making linear movements, and the complex combination of axes rotating to do what we could consider a simple task. Locate real world geometry in digital model space. Use KUKA|prc's simulation to verify your code before running it. Consider the differences between your intended effects of your simulated code versus how they might need to be adjusted for the real robot.

//Feedback on aMAZEing assignment//

With this assignment, the students had the first interaction with the robot. In the first place, they used the teach pendant[1] to address the kinematics by pushing buttons manually (Fig. 3.11). The teach pendant allowed them to choose the coordinate systems that they wanted to use as a reference. In doing so, they understood under which circumstances it is more advantageous to use either one reference system or the other. Then, the students familiarized with basic robo-programming by setting a linear and planar toolpath within the geometry of a maze.

1 A tech pendant is a handheld device used to control the motions of a robot manually, step by step. They could be wired or wireless.

Fig. 3.11 Students working on the first assignment aMAZEing. Above: Nathan Ickes. Below: Irene Missler.

LightBright

//Project003 - LightBright//

The LightBright project highlights the three toolpath move types available to the robot through KUKA|prc. Create abstract 3D geometry in rhino and/or grasshopper. (no words, faces, or other silly things). KUKA|prc uses points to define geometry so you will need to understand how this translates from your intent to the understanding of the software.

//Low Level Skill Acquisition//

You will learn the differences between PTP, LIN, and SPLINE moves as generated by KUKA|prc. We are disregarding CIRC for this assignment.

//Higher Level Skill Acquisition and Tooling//

Notice the effects that approximated positions have on your toolpath. Compare the speed of the robot as it executes the different movement types. Be able to compare the operations. Be able to differentiate the geometrical operations and how they might be applicable to different types of future work. This project will use a white LED tool designed and provided for the class. The tool has already been defined in the provided KUKA|prc file.

//Feedback on LightBright assignment//

The assignment LightBright asked to produce long exposure photographs drawn with light where the robot did not touch material. To perform the exercise, students installed an LED light on the robot's head. Then they took a photo in bulb mode for the duration of the kinematics. The result is a geometric composition through which to visualize the effects of algorithmic programming (Fig. 3.12). Association was made with the themes of technological production between the exercise and the motion studies of the industrial engineers Frank Bunker Gilbreth and Lillian Evelyn Moller, who was also a psychologist. Gilbreth had developed a study method to analyze the movements of workers on assembly lines in the 1910's. By taking long exposure photos, the mechanical sequence and timing of repetitive tasks was possible,[1] in order to intervene on their rationalization, instead of making changes to the work environment to improve the efficiency of the production process. With the same logic and according to the result to be pursued, students were able to rework the code and set the software settings deciding whether to optimize the execution time or the number of axial rotations to complete a given action. The time component is therefore the fourth dimension in three-dimensional space to be taken into account in the production design phase, dictated by mechanical motions.

1 Exposure: Motion Efficiency Study by Frank Gilbreth, in *Design Observer*: https://designobserver.com/feature/exposure-motion-efficiency-study-by-frank-gilbreth/39272.

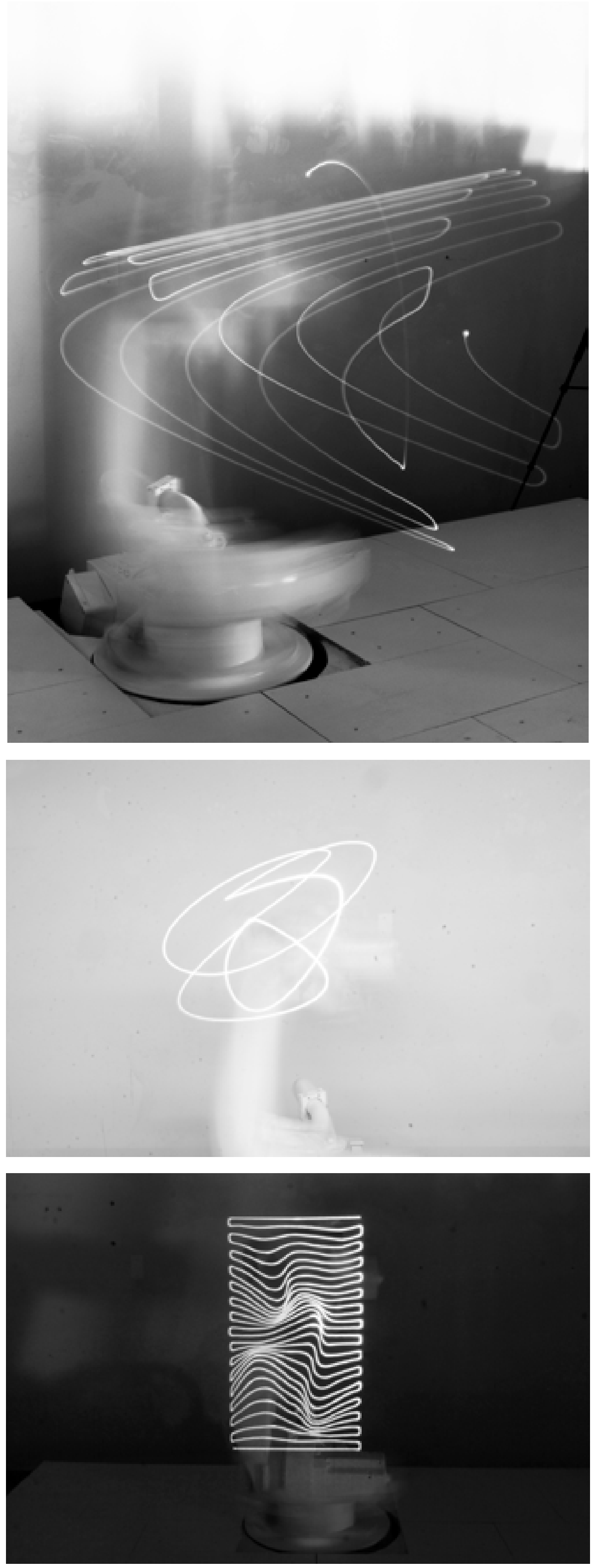


Fig. 3.12 Some robo-light-painting exercises. Above: project by Michael Zonca, Zakia Hunt, Francisco Landeros, and Aaron Wrubel. Center and below: works by the author.

ModelScope

//Project004 - ModelScope//

The ModelScope project requires you to increases your precision and ability to specifically locate your model and Bianco in physical space. Using a USB modelscope you will be able to see realtime what the tip of the robot "sees". Given this augmented vision you will create a fly-though video of a physical model.

//Low Level Skill Acquisition//

In order to complete this project, you will need to digitally approximate a physical model, locate that model in the work cell and design a path that controls movement, depth of field, orientation, and field of view.

//Higher Level Skill Acquisition//

Consider what is gained with the precision offered by the robot. Is it possible for you see what you couldn't see before? What story will you tell with the video? What techniques can you borrow from cinematography?[1]

//Feedback on ModelScope assignment//

For teaching purposes, exercises have been structured to manage the complexity of design in three-dimensional space. The students installed on the robot head a snake camera (Fig. 3.13) and designed its movements around ad object to record a short video. Through basic robo-programming they could control and modify several parameters, from speed, to inclination angles, to loops. In continuity with the previous assignments, the exercise didn't require to touch any material. Conversely, the students built skills on setting linear kinematics, splines, and mixed toolpaths in the three-dimensional space.

Fig. 3.13 Students working on the ModelScope assignment. Project by Nathan Ickes and Jacob Croop.

1 The Box by Bot and Dolly: https://www.youtube.com/watch?v=lX6JcybgDFo. The short film documents a live performance that consists in project images on moving objects. All content was captured entirely in camera.

PinHead

//Project005 - PinHead//

Project005 introduces robotic placement and assembly. We will also operate with a collaborative human and robotic approach for this module. While this is not yet construction you should begin to get a sense that robots can be used to accurately pick up and position elements.

//Low Level Skill Acquisition//

Project005 asks you to place finish nails normal to a given surface with the heads uniformly offset from the surface. The nails will be embedded 1/3 of their length.

//High Level Skill Acquisition//

This project begins to articulate the notion of repetition and the aesthetic quality of high quantity. If robots can be used for the 4 Ds (one of which is dull), imagine the impact or affect of 5Xs as many nails in the same size surface. Also look at the repetition required in large buildings such as the placement of glazing or facade panels. Can you begin to imagine the installation carried out robotically?[1]

//Feedback on ModelScope assignment//

For this assignment, students were asked to use the robot to perform a repetitive task on a variable volume. They programmed the robot to guide the insertion of nails at regular intervals in the normal direction to a doubly curved polystyrene surface. A magnet was embedded in the end-effector, which acted as a gripper. The toolpath was structured in the steps: a (home position), b (normal direction towards the target point), c (insertion of the nail in the target point), d (retraction), e (pause), and repeat (Fig. 3.14). The pause gave time to the students to feed the robot with a new nail and start over. Not only the normal direction, but also the depth of insertion on the foam was considered. In this way, the concept of customized repetition was explored.

1 Laser drilling - Universal Robot for industrial automation in harsh operating environments: https://www.youtube.com/watch?v=CS0bmXW43Us. The reference for the assignment was the project Parsimony by Charles Aweida: https://vimeo.com/287973492.

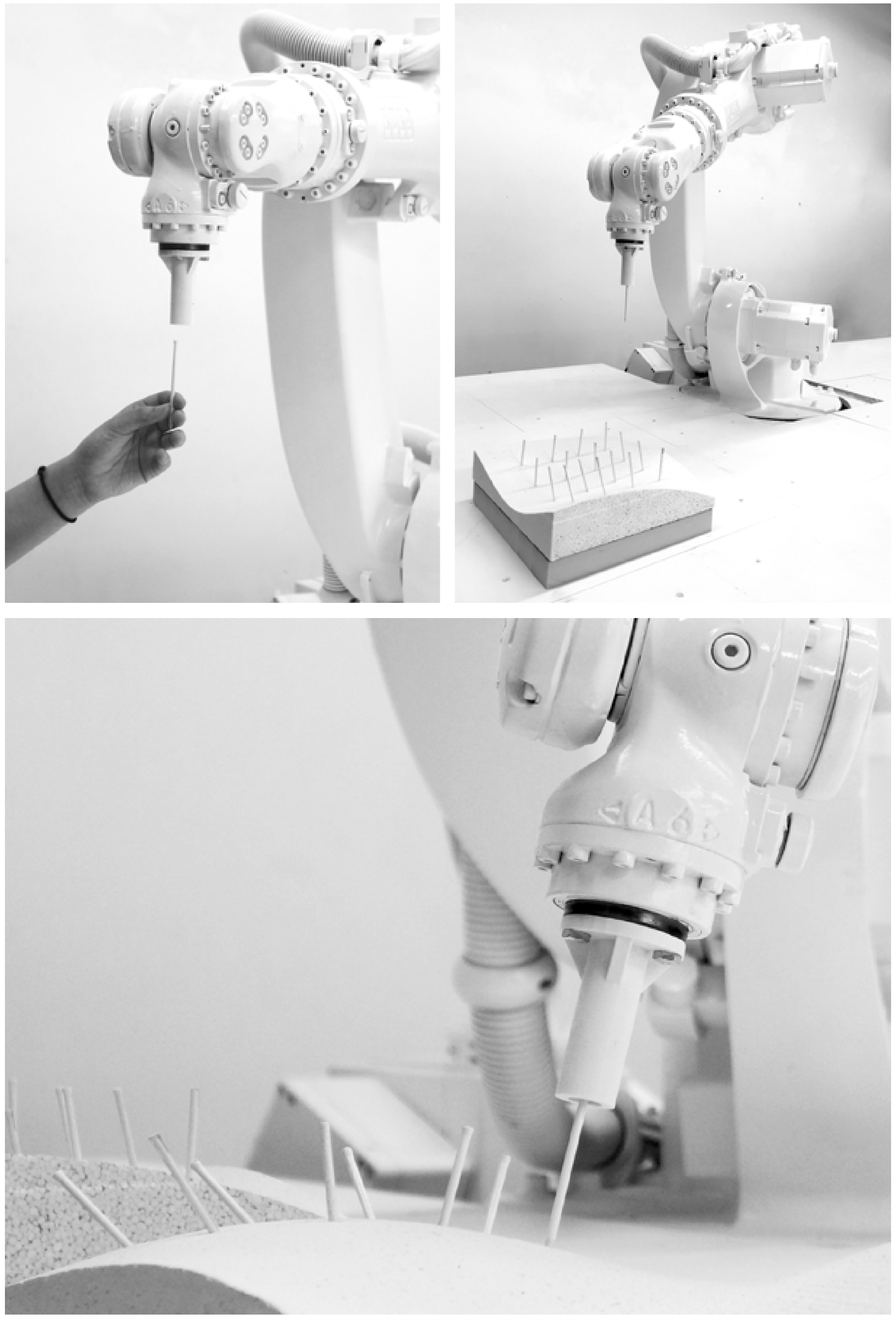


Fig. 3.14 The PinHead assignment. Human-robot collaboration during the execution of the repetitive toolpath.

flowLines

//Project006 - flowLines//

The intent of SurfaceFlow is to develop the concept of precise oriented robotic toolpaths. The LiteBright project maintained a static relationship between the light source (tool) and the camera and ModelScope introduced orientation with a camera position and camera target. This assignment requires more specificity between the tool and the geometry through the need to keep a pen in contact with a complex surface. By carefully controlling the distance between pen and surface line weights are possible.
Your team will be given a milled surface. Your team must draw a series of flow lines (at least 3000 mm of curves) on the surface using a sharpie and a custom pen tool that you will design and fabricate.

//Low Level Skill Acquisition//

-Oriented tool geometry
-Teaching a tool to the robot (setting tool lengths)
-Creation of combined and multiple toolpaths.

//High Level Skill Acquisition//

This project challenges your team to develop very specific and complex robotic toolpaths.

//Feedback on flowLines assignment//

Building on the previous assignment, flowLines was implemented by requiring the robot not only to reach single target points but to draw a path with continuous lines.[1] Using robotic fabrication, the concept of iteration and repetition no longer requires standardization. Students explored flexibility afforded by robots through the development of their own custom end-effectors (Fig. 3.15). The robot held and positioned custom tools with dexterity and precision.

1 Kuka Robot Drawing: https://www.youtube.com/watch?v=2J4fcLve1y4. This project was used as a reference for the assignment.

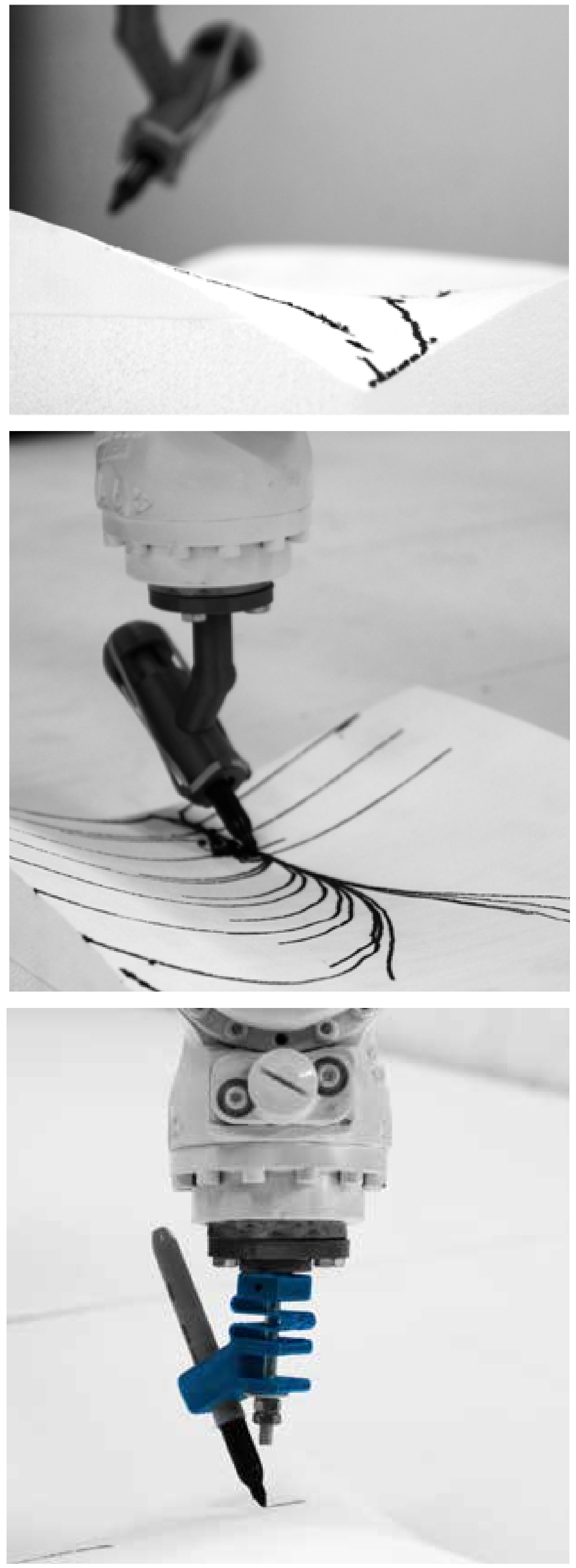


Fig. 3.15 Some end-effectors designed by the robo-class students. Above and center: project by Michael Zonca, Zakia Hunt, Francisco Landeros, and Aaron Wrubel. Below: project by Irene Missler, Eunpyeong Kim, Trent James, and Matthew Weyhmiller.

hotWire

//Project007 - hotWire//

The intent of hotWire is to extend the relationship between generative design (grasshopper in form making) and using the robot to prototype iterative physical models. We will define a simple framework and create a large population of forms.[1] This assignment introduces the hot wire tool for cutting foam.

//High Level Skill Acquisition//

Stereotomy (from the Greek: στερεός (stereós) "solid" and τομή (tomē) "cut " is the art and science of cutting three-dimensional solids into particular shapes. While this is a very old process, we will speculate on its advancement through the use of digital design and robotic cutting. If design is tied to iteration and testing, a good design could be the result of testing more iterations and learning from them. If we can automate aspects of the design and output process, could we speed up our design process, explore more territory, or get greater feedback? This assignment ponders the ability for a young designer to show up to studio pinup with 20 models to present to the instructor when your classmates show up with three.

//Feedback on hotWire assignment//

Once the technical foundations were laid for the course through simple and direct exercises, it was possible to approach the exploration of speculative architectural models. For this more complex work a hot wire cutter was installed on the robot as an end-effector. The purpose of the assignment was to explore through concept tests the study of stereotomy at the scale of architectural models. Students were asked to design cutting plans to be performed on 10cm by 10cm by 10cm cubes. Each cube had to be cut at least 5 times. No indication was given on the characteristics of the cutting plans, which could be single, composite, straight, or curved. Through algorithmic design it was possible to iterate the formal generation process, change the cutting sequences, and simulate the result. Each working group produced 20 models and each iteration was informed by the model scale previously created (Fig. 3.16). Acting directly with the hot wire on the polystyrene, the students also had feedback from the material itself. Based on the result obtained, they were able to optimize the robotic programming by modifying the cutting temperature or the kinematics speed. From the volume, we moved on to the design of the production sequences, which take place without a privileged direction, from bottom to top or from outside to inside, but according to the logic of process efficiency, to confirm the quality of the result. Robotic fabrication has made it possible to quickly produce repetitive or non-standard complex shapes that are difficult to produce by hand based on three dimensional accuracy, with no limits to creativity.

1 Reference used for the class: Volynets, I., 2017. Benjamin Wilke (ed): Stan Allen: Four Projects.

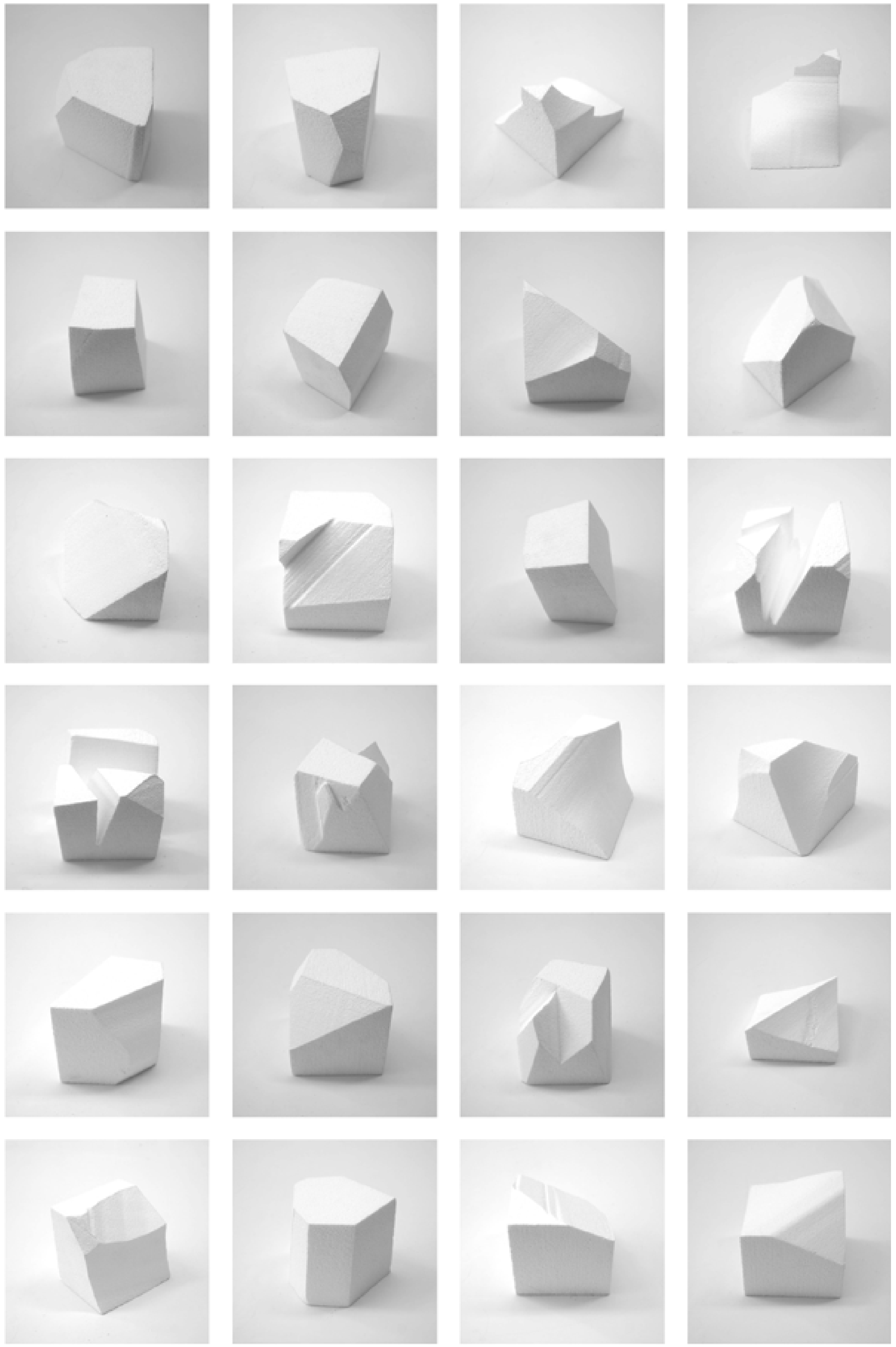


Fig. 3.16 The population of foam scale models produced by the students through robotic hot wire cutting.

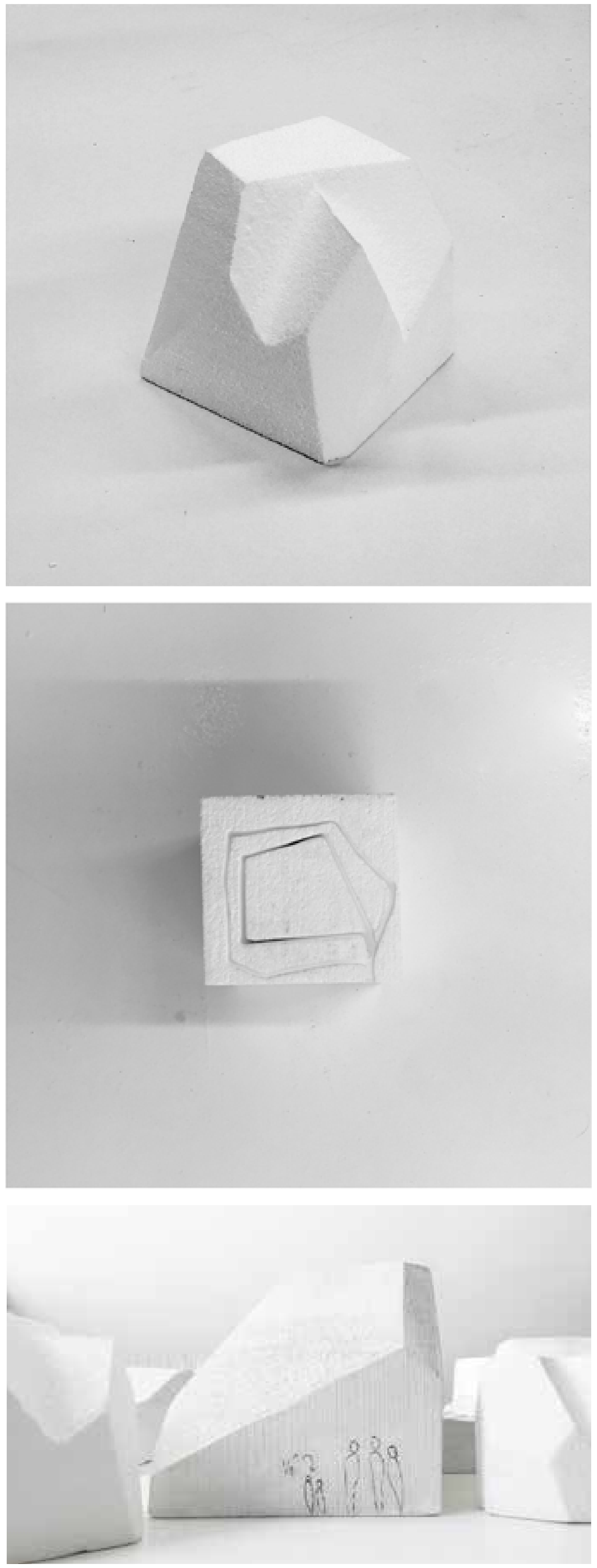


Fig. 3.17 Examples of robotic hot wire cutting to explore model making by working inside and outside the matter.

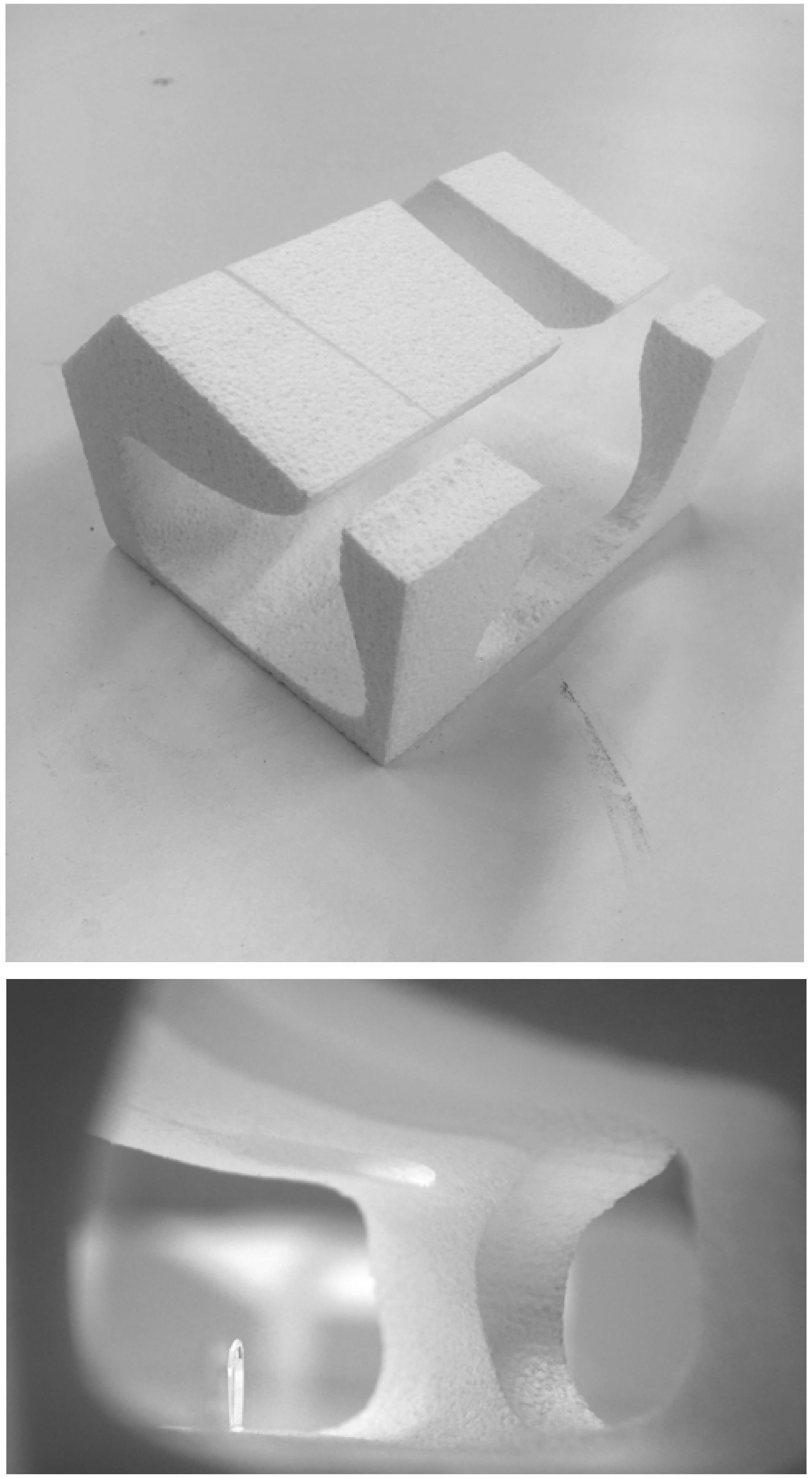


Fig. 3.18 Translation of the meta - scale models to more refined ideas of architecture through robotic making.

formWork

//Project008 - formWork//

Project008 is a combination of the skills obtained thus far in the RoboFab course. The intent of this assignment is to create and explore complex architectural models. We will cast plaster in forms cut out of foam cubes (6"x6"x6") using the hot wire cutter. Then we'll record a robotic video flying through the negative spaces.

//Low Level Skill Acquisition//

This project aims at enhancing the understanding of complex geometric relations between mass and void in architecture. Robot programming will allow us to produce multiple iterations that are constantly improving in design processes. Once the form is cut, you will be presented with unique subtle elements that are not always evident in the digital environment. These shapes can be combined to explore new design paths resulting in volumes based on critical thinking.

//High Level Skill Acquisition//

This assignment further explores the possibilities of robotic - foam hot wire cutting. We will master how to work inside a study material, rethinking the process of material subtraction. We will work with a very simple set of constraints where we will intersect two extruded shapes resulting in a complex combined form.[1] From a robo - programming perspective, the shapes will be very simple to program which will allow for maximum iterative testing. The final set of deliverables will be a video documentation of the plaster volumes. You are to record a video by controlling the robot. The documentation will increase our understanding of the forms and their proportions in our creative design process.

//Feedback on formWork assignment//

The final project required the students to use the hot-wire cutter to produce foam formwork for casting a plaster model (Fig. 3.19). Not only was there an inversion of solid and void, but the assignment added a secondary material process of casting. The students generated multiple complex models, always starting from a solid cube and working on doubly intersected voids. The models were displayed as part of a final exhibition of work with human scale figures emphasizing the desire to view the work not as desktop objects but proto-architectural explorations. The students could learn different relationships between machine and matter. The students composed the formwork in different ways to explore multiple design possibilities.

1 Biennale di Venezia, Central Pavilion. Scale models by Aires Mateus: https://divisare.com/projects/318837-francesco-galli-15-biennale-di-venezia-central-pavilion.

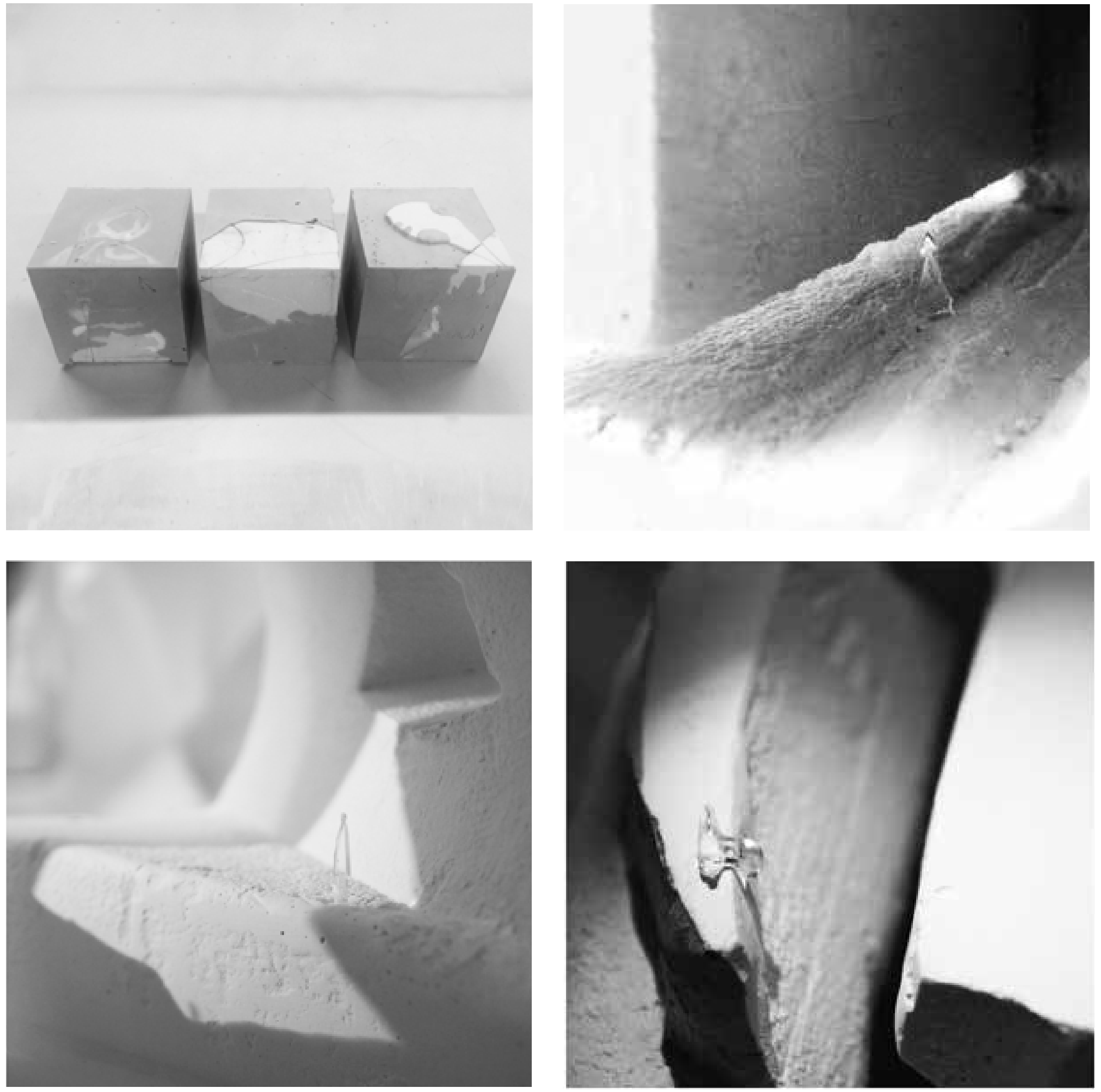


Fig. 3.19 Plaster scale models made by the students for the final assignment of the robo - class. Robotic hot wire cutting was used for the production of customized frameworks.

Fig. 3.20 Final exhibition with all material produced by the students over the (robo) digital fabrication class. Spring semester. Academic year 2018/2019. LTU-Coad.

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PART 2 STATE OF THE ART IN DIGITAL CH

4 Openness to new technologies for the conservation of Cultural Heritage

ABSTRACT

The state of progress of technology in the construction sector has led to the definition of new formal paradigms and to the exploration of innovative materials, generating new design processes, and realization paths. The introduction of non-standard technologies pushes architectural thinking to move from already established areas to expand traditional perspectives. The architectural debate in this regard encourages further reflection when the object of study is an architectural pre-existence of historical importance.

The interventions and the necessary conservative approaches defined to transmit the historical assets to future generations are supported by a solid tradition that constitutes the foundation of the discipline of the conservation of monuments. In the current context of digital transformation, it is necessary to evaluate both technology and culture. There is an acknowledgment that the diffusion of technologies will inevitably pass from the global scale to the local scale and lead to the eventual transformation of the notion of craftsmanship.

Culturally, in the state of the art, there are moments of openness in which to find a confirmation of legitimacy in the elaboration of new methods of intervention on historical assets. Furthermore, in order for the technique not to prevail over the cultural approach, it is necessary to develop a critical approach that clarifies the relationship between skills and technology advancement. This analytical path is driven by contradictions concerning architectural composition, as the term "digital" refers to the possibility of producing outcomes that resort to globalized design languages. In contrast, the search for genius loci in the post-digital era is a conversation that is still open and worthy of study in the academic field related to techniques, tools, and materials.

Keywords: *Architectural Heritage, Restoration, HBIM, H2020, Digital Workflows, Architect Master-Builder*

4.1 Traditional approach to Architectural Heritage

"Even a brick wants to be something. It's important, you see, that you honor the material that you use. You can only do it if you honor the brick and glorify the brick instead of shortchanging it [Louis Kahn, 1998]

Recovery interventions[1] are the result of a historical and critical reflection. From the characteristics of a historic building it is possible to translate operational and technical choices. "Hence the need for the progressive refinement of technologies, obtainable through the scientifically controlled use of executive and material systems, and the need for a wide dissemination of interdisciplinary collaboration" (Carbonara, 1997). From the basic conceptual choices derive the various operational proposals. These proposals then draw on technological alternatives that will be examined according to the nature and history of each single work, guaranteeing the perpetuation of the asset through the expressive aspects "of those minimal, indispensable additions and modifications that will be necessary to make" (Carbonara, 1997). The principles of distinguishability and authenticity avoid any attempt at imitation in style or historicist falsification. The dialectic between history and the dialectic of restoration is formulated openly by Cesare Brandi who makes it the cornerstone of his theoretical work. The publication of the book *Theory of Restoration* marked a pivotal event in the debate on the conservation and restoration of Cultural Heritage, to the point of making it an indispensable reference in the principles sanctioned by the 1972 *Restoration Charter*, issued by the Italian Ministry of Education.

The guiding principles or operational precepts that emerged since the mid-eighteenth century were then consolidated into the formulations of "scientific restoration" and are now generally accepted:

1. the distinctiveness between additions and original parts, in order not to distort the reading of the "historical text" and to guarantee instead a clear interpretation;
2. the reversibility of the intervention (from the Latin "revertere", or the feasibility of the return of a work to the status prior to it) for which the possibility of future corrections or adjustments of the work is not precluded, without jeopardizing the work. Heritage interventions are in fact driven by

1 The chapter of the dissertation "Cultural assets in the field of restoration" was double blind peer reviewed and published in the book *Digital Cultural Heritage*, by Springer International Publishing as part of the Lecture Notes in Computer Science book series (LNCS, volume 10605). The single-author paper, affiliated with Ferrara University, "The Conservation of Cultural Heritage in Condition of Risk, with 3D Printing on the Architectural Scale" (pp.239-256 - DOI 10.1007/978-3-319-75826-8_20) was the follow up of the Final Conference of the Marie Skłodowska-Curie Initial Training Network for Digital Cultural Heritage, ITN-DCH 2017, Olimje, Slovenia, May 23–25, 2017.

a "critical hypothesis" and as such must always be verifiable and amendable;

3. the expressive authenticity, for which any element is added must be a clear testimony of the present time, without however its juxtaposition to the work proves jarring;
4. the slightest intervention, limiting itself to intervening only when this is indispensable for conservation, altering the existing building as little as possible;
5. the physical-chemical compatibility between the original materials and those used in the intervention.

These principles result from an evolution of conservative thinking that has been codified in the Renaissance, with the affirmation of the historical-philological approach of the study of the past (Lorusso et al., 2002). This makes it possible to evaluate the works as documents without this preventing the intervening on them to modify them in the name of current events (Carbonara, 2007). In the seventeenth century, this approach is countered by the thought that the stratifications that are determined on the monuments produce on the same a redevelopment that cancels the previous forms (Conti, 1988). In the eighteenth century, together with the affirmation of archaeological science by J.J. Winckelmann, a decree is issued for the preservation of monuments by the French National Convention which initiates the modern conception of restoration of monuments.

The nineteenth century is marked by the theories of Viollet-le-Duc in contrast to those of John Ruskin (Dalla Costa and Carbonara, 2005). Viollet-le-Duc affirms the validity of the stylistic restoration, which ignores the passing of time and is aimed at recovering the formal values of the era and the geographical location of the monument. Ruskin on the other hand supports the restoration of conservation, as arbitrary interventions constitute tampering (Chatterjee, 2017). To this end Ruskin proposes to favor maintenance interventions to slow down degradation and to limit interventions on monuments to the operations necessary for their consolidation. The typical Italian vision of modern restoration is addressed at the end of the nineteenth century by Camillo Boito. In this context a theoretical vision called scientific restoration or "third way" is generated (with respect to the stylistic and conservative approach). It is based on the principle that it is necessary to know what is being restored in order to carry out conservation: the study of the monument aims at the reconstruction of its historical event.

The interventions carried out on the monuments are brought back to four main types:

- consolidation, that is all the interventions aimed at ensuring the stability of the structures by means of traditional and innovative materials;
- recomposition (anastylosis), by reassembling the parts that collapsed with the original consolidated materials;
- release, or the removal of added parts considered disfiguring for aesthetics or dangerous for statics;
- integration and renewal, through the integration of missing parts or the addition of parts that never existed.

The positions of Boito evolve into the thoughts of Gustavo Giovannoni, who in the framework of scientific restoration theorizes philological restoration. The restoration must restore the functionality of the building and where additions are necessary to make this possible, they must reproduce exactly the missing forms, but with simplified language, by virtue of distinguishability. In Europe for the first half of the twentieth century, the theses of Boito and Giovannoni have a decisive weight in the drafting of the Charter of Athens of 1931 and of the Italian Charter of the restoration of the monuments of the following year. In the 1940s, the theory of restoration evolves with the convictions of Cesare Brandi (together with Renato Bonelli and Roberto Pane), whose vision is based on the recognition and respect of the work both in its historicity and in its aesthetics (Brandi, 1963). This leads to curbing the reconstruction interventions and to enhancing the preventive operations. The Italian tradition has always maintained a wide debate on the subject of heritage conservation. Among the most influential current position is that of Giovanni Carbonara, who indicates a critical-conservative director. Conservative, because it requires the monument to be transmitted to the future. Criticism, for the conviction that every intervention constitutes an episode in itself, not classifiable in categories. The restoration of monuments is a strictly scientific and philologically founded activity whose aim is the conservation and a clear and historically correct reading of the works concerned. The qualifying element of the restoration operation is not just conservation, understood rather as a preventive action, but not even the simplistic facilitation of the reading of the building. Restoration means a direct intervention on the work, including also its possible modification, always under a technical-scientific and historical-critical direction.

Athens Charter (1931)

In 1931, during the First International Congress of Architects and Technicians of Historic Monuments, the drafting of the *Athens Charter*[2] (Corbusier and Eardley, 1973) laid down the basic principles for the conservation of Architectural Heritage. 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). This document has meant the theorization of fundamental principles:[3]

- the idea of a common world heritage;
- the importance of the contextualization of monuments in their local history;
- the principle of integrating new materials in conservative interventions.

Italian Restoration Charter (1932)

The *Italian Restoration Charter* (Consiglio Superiore Belle Arti, 1932) issued at the Ministry of Education, showed a greater openness towards using the latest technologies for scientific restoration (art.2).

2 *Athens Charter*, full document text (1931): https://www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/167-the-athens-charter-for-the-restoration-of-historic-monuments.

3 *General Conclusions of the Athens Conference* (1931): https://www.getty.edu/conservation/publications_resources/research_resources/charters/charter02.html.

It was the first official Italian guideline in the field. It was adopted in 1932. The Charter remained unmovable on the subject of anastylosis. It viewed archaeological ruins as too remote from our traditions and our present civilisation (art.3). This Charter affirms the principles expressed in Athens and suggests to exploit technology in order to carry out the so-called scientific restoration, based on the conservation of the good in deep respect for the historical-aesthetic characteristics of the work.

Venice Charter (1964)

The *Venice Charter* of 1964[4] is a post-war document that codifies internationally accepted standards of conservation practice relating to architecture and sites. It set forth principles of conservation based on the concept of authenticity and the importance of maintaining the historical context of a site or building.[5] The document, in continuity with the *Italian Restoration Charter*, also expressed itself regarding anastylosis. 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 determined of universal principles on the methodology of architectural restoration, focusing on the technical aspects necessary to carry out recognizable conservative interventions, based on the idea that "the process of restoration must stop at the point where conjecture begins" (art.9). The *Venice Charter* introduced the concepts of tangible and intangible heritage. It is still the most influential international conservation document.

Italian Restoration Charter (1972)

The terminology developed in the context of restoration 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. It was issued as a circular by the Ministry of Public Education (Ministero della Pubblica Istruzione, 1972). The Charter of 1972 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 according to new technical and scientific acquisitions for restoration works on Architectural Heritage, but preferably if minimised in comparison with the volume of pre-existence (art.9).

4 *Venice Charter*, 1964: https://www.icomos.org/charters/venice_e.pdf.
5 *Cultural Heritage Policy Documents*, The Getty Conservation Institute: https://www.getty.edu/conservation/publications_resources/research_resources/charters/charter12.html.

Declaration of Amsterdam of (1975)

The *Declaration of Amsterdam*[6] of 1975 took into account the risk conditions that threaten the European Cultural Heritage and represented a partial step back in conservation theories. It was adopted by the Ministers Committee of the European Council three years after the UNESCO List of World Heritage in Danger was drafted. 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".

Washington Charter on the Conservation of Historic Towns and Urban Areas (1987) - Lausanne Charter for the Protection and Management of the Archaeological Heritage (1990) - Cracow Charter (2000)

The documents 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),[7] archaeological sites (*Lausanne Charter for the Protection and Management of the Archaeological Heritage* of 1990),[8] and built Heritage and landscape (*Krakow Charter* of 2000).[9] In particular, the *Lausanne Charter* "lays out general principles for investigation, maintenance, conservation, and reconstruction of architectural heritage. It also notes the role of high academic and professional standards in relevant fields of expertise and the need for international cooperation."[10]

ICOMOS Charter, Principles for the Analysis, Conservation and Structural Restoration of Architectural Heritage (2003)

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*[11]. It is 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 relevant because it proposes detailed guidelines for heritage

6 *Declaration of Amsterdam*, 1975: https://www.icomos.org/en/charters-and-texts/179-articles-en-francais/ressources/charters-and-standards/169-the-declaration-of-amsterdam.
7 *Washington Charter on the Conservation of Historic Towns and Urban Areas*, 1987: https://www.icomos.org/charters/towns_e.pdf.
8 *Lausanne Charter for the Protection and Management of the Archaeological Heritage*: http://wp.icahm.icomos.org/wp-content/uploads/2017/01/1990-Lausanne-Charter-for-Protection-and-Management-of-Archaeological-Heritage.pdf.
9 *Krakov Charter*: http://smartheritage.com/wp-content/uploads/2015/03/KRAKOV-CHARTER-2000.pdf.
10 Cultural Heritage Policy Documents, The Getty Conservation Institute: https://www.getty.edu/conservation/publications_resources/research_resources/charters/charter43.html.
11 *ICOMOS Charter*, https://www.icomos.org/charters/structures_e.pdf.

restoration. It suggests remedial measures and a methodology for an effective supervision of the projects. It states: "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). The Charters drafted at the beginning of the century postulated the basic principles of restoration. They addressed the discipline mainly for conservative purposes. This is evident if we consider that the committee members were solely European. Conversely, recent Charters are better disposed toward the use of new and experimental technologies for construction in architecture.

New technologies do not only represent an ordinary improvement to existing restoration methods. Rather, they upgrade the traditional construction processes, in respect of the principles expressed by the Charters. The affirmation of the global digital infrastructure that characterizes the contemporary era has brought about a change in processes, with repercussions on project outcomes. Digital workflows have brought design and construction closer together, not limiting the architecture to the mere representation of technical and executive drawings. This context led to the definition of a new programmatic document, the Declaration of Cooperation on advancing digitization of Cultural Heritage, signed in 2019 by the Member States of the European Union. Among the main operational objectives of the declaration is the conservation of the works for transmission to future generations through their digital documentation. The contents will be discussed in the following paragraphs.

4.2 Innovating technology and managing tradition

"Robotic fabrication is the future, to complement conventional construction methods and craft-based fabrication. Chisels and robots do not exclude each other; they each have their place. As robots re-enter construction it is crucial to know when and when not to use them [M. Bechtold, 2010]

The already visible results of the Fourth Industrial Revolution and the era of the Digital Transformation on the doorstep, suggest that in the near future the construction sector will appropriate new operational tools. The spread of automatic single and multi-tasking industrial machines, drones and large-scale instruments for the additive production of architectural units is conceivable in the near future. The flexibility of their use and new production methods could allow for new, non-sequential recovery site processes with temporal and quantitative gains. The potential for optimization is also inherent in the

qualitative control of the result. This could lead to increased management of dimensional tolerances where "old mechanical machines were based on standardization whereas new digital machines are based on nonstandard modes of production and both technical paradigms can be put to good use, if one understands the limits and the potential of each" (Carpo, 2010). These systems will bring innovation with regards to the production chain of components (structural and non-structural) and the installation systems. With a dwindling on-site human workforce designers may begin to question the proportions and dimensions of the discretized elements that make up historic buildings.

The design approach that leverages innovative tools is in contrast with the artisan techniques that led to the construction of the original historical building. Old and new techniques can be viewed as a formal counterpoint and comparison of traditions. The use of digital fabrication may constitute a further element of dialogue with past buildings. The use of traditional procedures or the exploration of new processes are two design possibilities, which can be kept parallel or hybridized, as long as they always correspond to the fundamental restoration principles. The guidelines for each historically relevant project must determine their own legitimacy of intervention. This can be most difficult in instances where the state of degradation of the asset does not allow anastylosis. Regardless, every case must consider the following principles:

- minimum intervention (1931 *Athens Charter*, 1932 *Italian Charter*, 1964 *Venice Charter*, 1972 *Italian Charter*, 2000 *Krakow Charter*, 2003 *ICOMOS Charter*);
- reversibility (1972 *Italian Charter*, 2000 *Cracow Charter*, 2003 *ICOMOS Charter*);
- compatibility of the integration with the preexistence (1972 *Italian Charter*, 2000 *Krakow 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*);
- digital documentation (2003 *ICOMOS Charter*; 2019 *Declaration of Cooperation on advancing digitization of Cultural Heritage*).

Respect for the "case-by-case" evaluation logic remains the prerogative of the project, which is based on the knowledge acquired, the design experience, and the architect's critical ability. Through value judgment the architect performs transformations that take historical values into account (Tafuri, 1991) matching in the best way to the value of novelty (Dal Co, 2013).

The comparison of international research groups makes it is possible to imagine how robotic automation, based on digital projects, will be the key to permanently transform traditional construction sites. From this acknowledgment, there is a need to understand how robotic technologies can be deployed on existing recovery sites. The rigidity of the sequential building phases have already proved not to be fully responsive to the needs required by the construction site (Norsa and Missori, 2004).

The development of the discipline of restoration, which has the case-by-case decision-making approach as one of the foundations, makes the site become the place where the main design choices are made (Sposito and Germanà, 2004). This happens without the reference of a systemic pre-organization of the process that includes "knowledge, conservation and valorisation" (Sposito, 1995) to meet the needs of requirements and performance (Sposito and Germanà, 2004). This approach creates a predictive impossibility of the technical risk and the effectiveness of the processes. Among the virtuous attempts to fill this methodological gap, mention is made of the research carried out in Italy at the Department of Architecture of the University of Palermo. From the dissemination carried out in the disciplinary area of Architecture Technology, we find consistent proposals aimed at consolidating a systemic vision (Di Battista et al., 2006) of the interventions on the existing, both in the investigative process phase and in addressing the conservative process.

These proposals elaborate programming criteria (Della Torre, 2003) that take into account the time, resources, skills and technical complexity of the built environment in order to preserve material assets through conservation, protection and use (Cecchi and Gasparoli, 2010). As Maria Luisa Germanà explains[12] in the scientific paper "Technology and Architectural Heritage: Dynamic Connections" the innovations and the "unprecedented advances of scientific knowledge" (Schwab, 2017) introduced by the Fourth Industrial Revolution “provided the opportunity to apply a technological approach to the conservation of the architectural heritage and archaeological sites” (Germanà, 2019). Technological evolution and its repercussions in the field of Cultural Heritage in the two technical and theoretical instances are placed at the service of a process that already in 2004 had been theorized as "reliable conservation of architectural heritage" (Germanà, 2004).

Digital infrastructure ubiquity appears to be the lever for overcoming the procedural arrangements that still refer to traditional methodologies. Some consequences of this digital infrastructure influence are already visible in the new construction sector. It is expected that the use of on-site automation will increase exponentially within the next decade and that the processes will also be transferred to the field of architectural heritage. This can occur as a result of the operational transformations that derive from the reduction in device costs accompanied by the dissemination of knowledge on their use.[13] Supporting the transformation of industrial / construction technologies is the synergy with the relief process, both geometric and diagnostic, which contribute to the storage of knowledge on the building through non-invasive procedures. However, this level of digitization does not provide a practical toolkit in the decision-making phases and "cannot resolve certain critical conditions that remain in the process, both upstream and downstream" (Germanà, 2014).

From these previously mentioned instances emerges the potential of a smart reconfiguration of the recovery site. This reconfiguration is possible through a connection between material and digital offered by digital fabrication and through the translation of digital data (Gershenfeld, 2012) by means of additive manufacturing. While this may seem to be a disciplinary breach, it proves to be a forerunner of the technical advances being optimized at a global level. The operational flexibility of the robots open up opportunities for carrying out on-site construction processes, guaranteeing on the one hand respect for the existing building and on the other hand the possibility for the designer to respond coherently with respect to the architectural language. The interventions can be formulated on the basis of digital surveys that are processed in real time on-site, in which the physical merges with the digital in the so-called operational context of "phygital heritage" (Nofal et al., 2017).

The knowledge of the intellectual path that has brought the discipline of restoration to the present day is essential to elaborate the critical tools necessary to face the future transformations of the architecture designer profession. These transformations are now underway and constitute the sequel to the Digital Turn in architecture which involved the 1990s and early 2000s. The legacy of this paradigm shift is expressed with the introduction of computational thinking in project workflows, influencing forms and languages of physical outcomes. Afterwards, the post-digital era guided by the Fourth Industrial Revolution has set itself in such a way as to bring architectural design and production closer together, through the appropriation and modification of tools originally created for mass production.

The rapid development of additive and robotic manufacturing globally leads the architect to specialize with new skills. The use of digital fabrication encourages the architect to move away from classic logics and get closer to the subject (the thinker becomes a maker), which acquires digital intelligence through process information. This process will involve all the areas of competence in which an architect can operate, both for the new construction and for the intervention on the building. The introduction of new tools will also suggest a program of new design possibilities and intervention techniques for restoration. They will require an approach, rigorously case by case and in compliance with the five fundamental points mentioned at the beginning, able to define a dialogue between the history of the buildings and the operations of integration / restoration dictated by contemporary architect-craftsperson who designs with the digital material. In this digital transformation, an opportunity to express our time in the operations of integration of damaged artefacts can be seen, contributing to the stratification of history through a digital layer.

Digital craft opens up a wide field of architectural design options informed by the tools. The computer allows for increasing levels of specification and complexity. The output of this digital complexity can be taken up by the robot which can manipulate and arrange large quantities of material. Combining the digital design with robotic output creates a new quality of products, that are able to be highly specialized to the limit. If traditional craft involves an implicit knowledge of using materials, digital craft requires a precise description of material, process, and relationships. By formulating the digital description, the designer has explicit and direct control over machine output. Designing fabrication processes becomes an integral part of the architectural design. When the digital designer understands both the possibilities and limitations of the tools, new forms of expression can emerge.

12 Maria Luisa Germanà: https://www.unipa.it/persone/docenti/g/marialuisa.germana.

13 "8 Things Every School Must Do To Prepare For The Fourth Industrial Revolution", in *Forbes* (Bernard Marr): https://www.forbes.com/sites/bernardmarr/2019/05/22/8-things-every-school-must-do-to-prepare-for-the-4th-industrial-revolution/.

4.3 European research on the digitization of Cultural Heritage

"The digital revolution is leading to new and innovative forms of artistic creation while making culture and heritage more accessible and opening up new ways of enjoying cultural content [Tibor Navracsics, 2018]

In recent decades, European and International Cultural Heritage leadership intensified and broadened guideline definition and shared strategic actions for preserving the collective heritage. Additionally, the scientific community agreed that Cultural Heritage includes multiple orientations of meaning, concerning the nature of the heritage itself and the different approaches to its protection. UNESCO, the world's most authoritative organization for the promotion and protection of Cultural Heritage, was the first organization to explain the concepts of tangible and intangible heritage, as interconnected and complementary principles for the definition of a recognizable cultural identity.

The tangible heritage is the set of physical artifacts created and handed down through the generations as a testimony of creativity and collective human knowledge. Monuments, architectural artifacts, urban fabric of historic cities, objects produced by artisan knowledge, and archaeological sites are all documented and labeled as part of this tangible heritage.

The intangible heritage includes the progress of collective knowledge handed down orally and consolidated through the preservation of local traditions, social habits, and pervasive arts and crafts. Formally, the Convention for the safeguarding of the Intangible Cultural Heritage held in Paris in 2003, describes intangible assets as "the practices, representations, expressions, knowledge, skills - as well as the instruments, objects, art and cultural spaces associated therewith - that communities, groups and, in some cases, individuals recognize as part of their Cultural Heritage" (UNESCO, 2003).

These principles of tangible and intangible Cultural Heritage have been updated and continue to expand in content. The European Year of Cultural Heritage 2018[14] included an initiative aimed at disseminating the value of culture in its various representations as an invaluable asset. This initiative occurred in reaction to dangerous conditions of environmental, political and social conditions, to which Cultural Heritage has been increasingly subjected to in recent history. Natural assets and digital assets emerge from this initiative. Natural assets are the environmental contexts that can be protected for the peculiarities of the landscape, flora and fauna that characterize them. Digital assets are resources created in digital format or that have been processed in relation to specific assets with the aim of preserving them.

14 The mission of the European Year of Cultural Heritage: https://europa.eu/cultural-heritage/about_en. The aim of the European Year of Cultural Heritage is to encourage more people to discover and engage with Europe's Cultural Heritage, and to reinforce a sense of belonging to a common European space. Every Member State has sponsored a spin-off of their institutional online platforms. The Italian Agenda could be checked out at: http://www.annoeuropeo2018.beniculturali.it/.

The European community is formalizing the theme of digital assets by investing in strategic programs aimed at digitizing Cultural Heritage.[15] This digitization is viewed as an opportunity for raising awareness while also promoting local community economies. In the document Commission "Recommendation on the digitization and online accessibility of cultural material and digital preservation" published in 2011 in the *Official Journal of the European Union*, recommended: "an updated set of measures for digitizing and bringing Cultural Heritage online and for digital preservation should be recommended to the Member States. In that context, "the development of digitized material should be further encouraged in order to ensure that Europe maintains its place as a leading international player in the field of culture and creative content and uses its wealth of cultural material in the best possible way" (European Commission, 2011). Confirming the commitment made by the institutions in this direction, the "Survey Report on Digitization in the European Cultural Heritage Institutions 2012" (Stroeker and Vogels, 2012) states that 20% of the European museum-like collections have already been digitized. The institutions further aim to digitize the entire European heritage by 2025. This work will finance European projects and at the same time create collaborations with additional non-profit institutions.[16] Monuments to which a digital model already exists are equivalent to 7%. A strategy for further implementing data collections was addressed in 2014 with "The Digital Agenda Toolbox"[17] (European Commission, 2014) and in 2018 with "A New European Agenda for Culture" (European Commission, 2018).

The theoretical premises of this dissertation exists between the two instances of conservation of tangible and digital assets. This research is oriented to the enhancement of digital resources as documentation of the architectural Cultural Heritage. This work proposes an operational methodology in the field of the restoration of monuments that is based first in the collection of digital data. Subsequently the data then benefits the protection of tangible assets through means of experimental fabrication. Digital fabrication through additive production, is the connection point between the tangible and digital worlds. The research then takes the opportunity to reflect critically on possible future applications and workflows that make use of new technologies that are only now beginning to assert themselves in the construction industry. This approach to both tangible and digital conservation involves the possibility of working simultaneously with design and decorative details. Design applications can be found at the level of volumetric definition of damaged elements to be integrated in buildings of high testimonial value. Work on decorative details might be found at the level of architectural image by means of surface processing. New opportunities emerge from the digital data and its ability to be continuously verified, modified, and redeployed. Complete control results from this process because the design is never detached from the time or site of production.

15 European programs on the Digitization of Cultural Heritage: http://s3platform.jrc.ec.europa.eu/digitisation-of-cultural-heritage.
16 Digitaleurope is a private institution that operates and invests in Europe to take advantage of the Information Technologies and support digital cultural innovation: https://www.digitaleurope.org.
17 The Digital Agenda Toolbox: http://s3platform.jrc.ec.europa.eu/dae-toolbox.

The building restoration site is a very specific context of intervention that primarily involves detailed on-site, labor intensive work and precision on-site assembly. Because of the specific solutions required for the building restoration site it is difficult to incorporate standard construction components or typical construction practices. Architectural heritage restoration traditions are strongly linked to craftspeople, and these traditions are a threat to digital continuity in the project realization transition. Connecting the digital to the craft traditions on a contemporary restoration project requires an architect professional that understands the workflows as a designer, builder, engineer, and material scientist. That is a digital master-builder that brings together the modern fragmentation of the various architectural modes of practice "in a single mind, heart, and hand" (Kieran and Timberlake, 2004). Extending the notion of the digital master-builder would require the pursuit of an integrated design methodology in which creative and constructive aspects were considered part of a single process. Another innovative aspect lies in considering the architect as algorithm builder. In this case, algorithm builder would not only design geometries described by functional input related to production, but they would also manage the digital-real transition subtended by more complex mathematical relationships. The opportunity would be that these algorithms could simultaneously design both the output and inputs for digital fabrication operations.

This research is also defined by links to the productive aspects of architecture with an analysis of European requirements of prevention, conservation, or intervention of damaged buildings. With regards to these issues, the *World Heritage Convention* held in Paris in 1972 (UNESCO, 2005) is still a current reference for the European community. The outcome was the definition of the List of World Heritage in Danger,[18] constantly updated over the years, it keeps track of ongoing worldwide risk episodes facing the world's Cultural Heritage. The list follows precise criteria such as imminent or potential danger, based on socio-political and environmental stability "to inform the international community of conditions which threaten the very characteristics for which a property was inscribed on the World Heritage List and in order to encourage corrective action". 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 tangible and 16 natural, located worldwide such as historical centres, architectural buildings, and archaeological sites. In addition to circumstantial risk conditions, the UNESCO portal also explains the extent of the damage to the protected sites in the short and long term. Damage can be identified as punctual or widespread, on which total or partial loss of elements of the architectural volume depend. Furthermore, for these macro-categories general guidelines for intervention and appropriate reconstruction actions are suggested, aimed at preserving assets and transmitting formal unity to future generations.

18 UNESCO List of World heritage in Danger: https://whc.unesco.org/en/danger/. The list includes 53 properties (cultural, natural, and mixed sites) all over the world: 40% in Arab States, 30% in Africa, 11% in Asia and the Pacific, 11% in Latin America and the Caribbean, 8% in Europe and North America. The span time for the mapping of these sites is 1978-2019.

An example from recent news stories highlights the sensitivity towards the archaeological site of Palmyra in Syria. As a UNESCO heritage site since 1980 there has been an increase in the selection of endangered assets since 2013. Its most recent, formalized State of Conservation (SOC) of 2018 reports: "in summer 2016, important archaeological monuments of the World Heritage Site of Palmyra, were intentionally destroyed. Some losses are irremediable. Its state of conservation is deteriorating, which has suffered from both deflagration and destruction".[19] The most negative determining factors regarding the site are listed as follows: illegal activities, war, destruction, looting, serious weathering of many stone blocks due to capillary rising and variations in humidity and temperature, and lack of a management plan. The intervention guidelines start from the assumptions that "the emergency safeguarding of this site, the analysis of the available documentation, is an utmost priority. There is an ongoing need for a conservation and restoration plan to be developed that addresses fully the complex issues associated with this extensive multiple site and will allow for coordinated management and address the issues of expansion of the nearby town". While local and international authorities wait for the sites to be secure and accessible, they are working to collect photographs taken by visitors and tourists from different periods, through a wide information campaign. Authorities hope to use the photographs to quickly reconstruct digital three-dimensional models of the main monuments of the site using photogrammetric techniques. These instances have been studied in depth to understand how the most advanced automated and digital technologies for constructions can come into support in these emergency conditions. Digitization efforts are encouraged by the direction of the European community through the push for technological developments. The description of these operational and technological developments will be addressed in the following section.

The paragraphs immediately following will report the state of the art for significant European initiatives in the field of innovation and cultural dissemination in relation to the themes raised by this research. Critically examination will highlight possible overlaps of intent between the objectives of this research and the efforts already planned by the European cultural institutions. The Declaration Cooperation on Advancing Digitization of Cultural Heritage signed by the member states in 2019 marks a decisive cultural step in the heritage community. It is the result of the positive outcome of a package of projects developed to fund research by the European Union. The package of projects include the seventh (2007-2013) and the eighth (2014-2020) framework programs (Fp7-8), the latter better known as Horizon 2020 (H2020). It also represents a set of concrete guidelines that aim to provide a more operational direction than the purely theoretical nature of the Restoration Charts.

19 Unesco portals show the actions for the emergency safeguarding of the portico of the temple of Bel in Palmyra (Syrian Arab Republic). The statement continues: "An element of the structure of the Temple, the Portico, remained miraculously standing, testifying to the irremediable loss of this emblematic monument. Its state of conservation is deteriorating; rapid assessments show the destabilization of the structure and the fragile pilling of its constitutive stones, which has suffered from both the deflagration and destruction of the monument.The emergency safeguarding of this structure, the thorough analysis of the available documentation, sound assessment of the damages and its consolidation, is an utmost priority". For further information, see: https://whc.unesco.org/en/activities/903/.

4.3.1 Declaration of Cooperation on advancing digitization of Cultural Heritage

In anticipation of the definition of the next framework program (Fp9) 2021-2027 for European research and in continuity with the results of the work of Digital Europe, Creative Europe, and Horizon 2020, the member countries have signed a steering document to support digital growth Europe through interdisciplinary collaborations and the use of emerging technologies. This document is *The Declaration of Cooperation on Advancing Digitization of Cultural Heritage*, signed on the occasion of the *Digital Day* held in Brussels on 9 April 2019. The context in which this statement was published is relevant as the *Digital Day* is an event intended to enable the EU and interested Member States to pool efforts and resources with a view to accelerating digital developments in key areas such as supercomputing, digital industry, automated driving, big data, and AI that can bring tangible benefits to economies and societies. In particular, the 2019 discussion panel with political stakeholder from Member States' governments was dedicated to four areas there digital is expected to make a significant impact: Artificial Intelligence, digitalization of agriculture and rural areas, promotion of greater participation of women in digital, and cooperation on advancing digitization of Cultural Heritage. In the field of Cultural Heritage, it has been confirmed that 3D technologies are promising to restore the damaged fragile heritage. They also promote the development of interactive systems for documentation and dissemination such as augmented reality (AR) and virtual reality (VR).

The Declaration fully captures the momentum created by the European Year of Cultural Heritage 2018, under the direction of the Expert Group on Digital Cultural Heritage and European (DCHE). It is also part of the spirit of the Rome Declaration of March 2017, a purely philosophical and identity document. The Declaration affirms the shared commitment to preserve Cultural Heritage with the aim of promoting cultural diversity in order to strengthen European identity and create a sense of belonging. The signatories of the 2019 Declaration agree to step up efforts and pursue progress under three main pillars:

- a pan-European initiative for 3D digitization of Cultural Heritage artefacts, monuments and sites;
- re-use of digitized cultural resources to foster citizen engagement, innovative use and spill-overs in other sectors;
- enhancing cross-sector, cross-border cooperation and capacity building in the sector of digitized Cultural Heritage.

The guidelines for digitization follow a common standard aimed at a comprehensive documentation of 3D models to be archived or updated in open access through interoperable online platforms. Archiving facilitates the promotion of best practices, the development of technical skills for digitalisation, and leads to broader strategic use. Through these principles, the networks of companies active in the sector push themselves to deepen the possibilities offered by big data, artificial intelligence, augmented-virtual-mixed reality and 5G connection. The aim of this collective work is "to enable innovative use of digitized cultural resources, knowledge extraction, and more engaging experience of heritage content". The signing of this document marks an acknowledgment that the digitization of cultural assets is a priority for European institutions. The institutions believe in the need to strengthen the digital shift that is currently being asserted in all areas of research and high training. It is always from a European perspective that initiates the protection of assets at risk, documentation and planning of interventions based on circumstantial elements such as the budget, the qualitative and quantitative aspect of the damage, and the scale of the recovery project to be carried out. From here to the near future, it is expected that most of the cultural assets throughout Europe will be digitized (European Commission, 2016).[20] In parallel, this research highlights the need for investment in the development of operational tools necessary to ensure maximum quality of processing, control of time, control of costs, consistency with the theoretical conservative approach, and transmission of the Heritage to future generations.

4.3.2 Inception: Inclusive Cultural Heritage in Europe through 3D semantic modelling

Within the European WPs,[21] a project that has brought significant innovations in the field of Digital Heritage is Inclusive Cultural Heritage in Ewwwurope through 3D semantic modelling, conosciuto come Inception.[22] The project was developed in 4 years, 2015 - 2019, by a consortium of partners from ten European countries led by the Department of Architecture in Ferrara.[23] The Inception project was developed under the Work Programme Europe in a changing world – inclusive, innovative and reflective Societies.[24] The Inception project main aim is focused on "innovation in 3D modelling

20 A feedback about Italian effort on digitizing Cultural Heritage, based on the REPORT on the Implementation of Commission Recommendation 2013-2015, follows. Istituto Centrale per il Catalogo Unico (ICCU) coordinates the efforts of 1,575 libraries from Italy, Vatican State and Republic of San Marino. It manages several services to promote access to the Italian digital Cultural Heritage. CulturaItalia, http://www.culturaitalia.it/, published a core set of records which are available for reuse at the SPARQL end point: http://dati.culturaitalia.it/. Internet Culturale, the portal of the digitized content of the Italian libraries, gives an integrated access to 940,857 records http://www.internetculturale.it/opencms/opencms/it/, corresponding to over 10M digital objects from various databases and repositories. It is fully integrated with CulturaItalia. General and specialised users can search digital contents coming from different information sources. OPAC SBN, the online catalogue of the National Library Service, http://www.sbn.it, gathers 5,884 Italian libraries distributed in 97 local poles that share the cataloguing infrastructure giving access to over 15M bibliographic news that are being linked to the existing digital resource, currently 690,000 links. MANUS, a database of descriptions and digitised images of the manuscripts owned by the Italian public libraries, churches and private bodies and citizens, http://manus.iccu.sbn.it, catalogues manuscripts in Latin alphabet from the Middle Ages to the present, including correspondence. Documents and Images on WWI, http://www.14-18.it, an initiative by the ICCU currently contains about 330,000 images and archival material documenting WWI, +135% in comparison with the previous report.

21 European WPs: https://ec.europa.eu/programmes/horizon2020/en/what-work-programme.

22 The Inception project. Website: https://www.inception-project.eu/en.

23 The academic partners of the Inception project Consortium, in addition to the Department of Architecture of the University of Ferrara, include the University of Ljubljana (Slovenia), the National Technical University of Athens (Greece), the Cyprus University of Technology (Cyprus), the University of Zagreb (Croatia), the research centers Consorzio Futuro in Ricerca (Italy) and Cartif (Spain). The clustering of small medium enterprises includes: DEMO Consultants BV (The Netherlands), 3L Architects (Germany), Nemoris (Italy), RDF (Bulgaria), 13BIS Consulting (France), Z + F (Germany), Vision and Business Consultants (Greece). This research project has received funding from the European Union's H2020 Framework Programme for research and innovation under Grant agreement no 665220.

24 Call for Research Innovation Action - H2020 Reflective Societies: Cultural Heritage and European Identities,

of Cultural Heritage through an inclusive approach for time-dynamic 3D reconstruction (AR) of heritage sites and on the possibility to create an inclusive understanding of European cultural identity and diversity for an easy and spread fruition" (Di Giulio et al., 2016) "by stimulating and facilitating collaborations across disciplines, technologies and sectors" (Di Giulio et al., 2017). The complexity of the project can be summarized in 5 phases or actions.

- First action: setting up of a common framework and knowledge management. This step is related to the development of a common framework for catalogue methodology among stakeholder, scholars, technicians, citizens and governments through the identification of key requirements that contribute to meet Europe's societal objectives related to Cultural Heritage;
- Second action: advancement into the integrated 3D data capturing methodology. It is related to the integrated 3D data capturing, both as methodological procedure and optimized workflow of data capturing technologies and documentation instruments (Fig. 4.1);
- Third action: semantic modelling for Cultural Heritage buildings in H-BIM environment. It is focused on the identification of the CH buildings semantic ontology and data structure for information catalogue. Integration of semantic attributes with hierarchically and mutually aggregated 3D digital geometric models is set up for managing heritage information;
- Fourth action: development of the Inception semantic web platform. The open-standard[25] Semantic Web H-BIM Platform allows achieving the widest accessibility and interoperability, the use of three-dimensional models by researchers from different disciplines and non-expert users (Maravelakis et al., 2013), minimizing the difficulties of interaction with these kind of data, now accessible only by experts through the use of different software;
- Fifth action: deployment and valorization through different on-site and off-site applications for a wide range of users.

The importance of Inception as an example for this thesis lies in the innovative approach that has been developed in the context of the enhancement of digital data for architectural heritage (Logothetis et al., 2015). Inception highlights how Cultural Heritage is a stratification of information that cannot be made explicit through un-interpreted geometric data. This information may relate to the nomenclature of the technological units that make up the building, the pictorial or sculptural decorative elements, the modifications that occurred over time, any damage conditions, or documents that attest to the possible future conditions of risk for the integrity of the volume. To superimpose this information on the documentation obtained from the quantitative survey means to expand the archive of information available on a historical asset into a single digital infrastructure and to systematize the application of the BIM with the Heritage, or HBIM (Bonsma et al., 2016). The processing of such digital information, which can be structured according to photogrammetric images, meshes, point clouds, historical documents, allows the elaboration of digital models defined as semantics (Pauwels et al., 2013).

Reflective-7-2014, Advanced 3D modelling for accessing and understanding European cultural assets. CORDIS reporting on EU reseach results: https://cordis.europa.eu/project/rcn/196967/reporting/en.
25 Open standard in H2020: https://ec.europa.eu/research/participants/docs/h2020-funding-guide/cross-cutting-issues/open-access-data-management/open-access_en.htm.

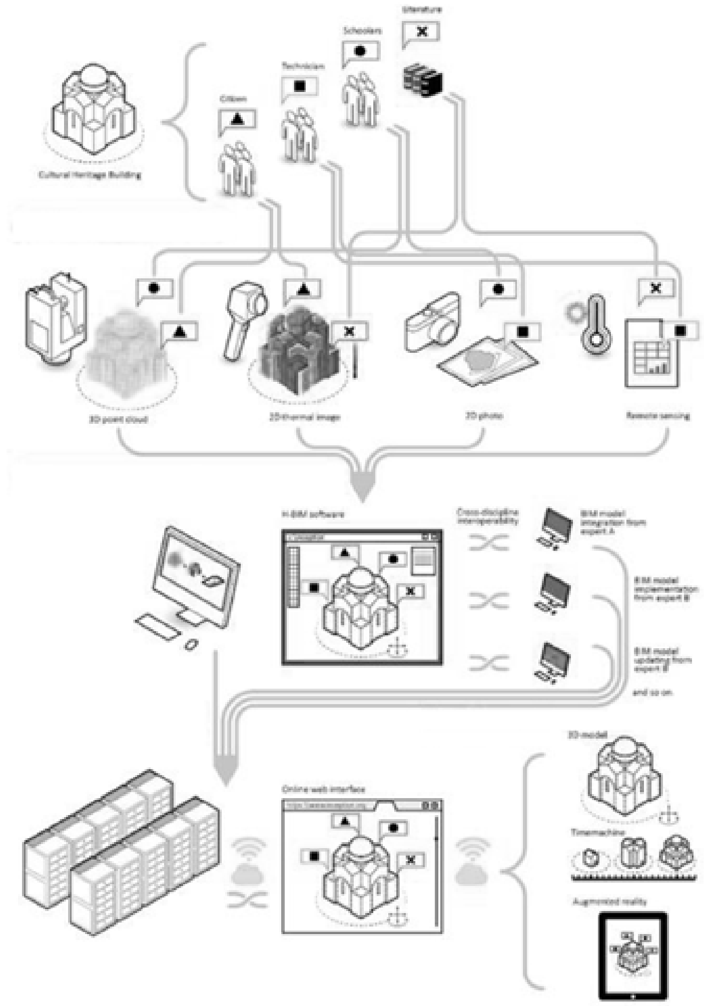


Fig. 4.1 The Inception's workflow: scheme of the project divided into five actions. Source: DI GIULIO, R., Maietti, F., Piaia, E., Medici, M., Ferrari, F. and Turillazzi, B., 2017. Integrated data capturing requirements for 3D semantic modelling of cultural heritage: the Inception protocol. In: *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*. Volume XLII-2/W3. 1–3 March 2017, Nafplio, Greece.

From the literature, there are several books that deeply analyze and summarize rules which were adopted in classical buildings (Fig. 4.2). Among the most known theoretical books from the past: *De Architectura* (*On Architecture*, published as *Ten Books on Architecture*) by Vitruvio, *De Re Aedificatoria* (*On the Art of Building*) by Leon Battista Alberti (Fig. 4.3), and *I Quattro Libri dell'Architettura* (*The Four Books of Architecture*) by Andrea Palladio. They influenced architecture all over the world for centuries.

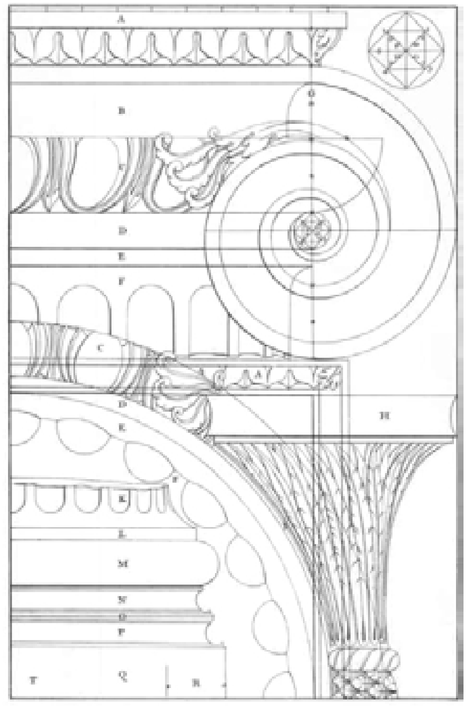
Nevertheless, local practices introduced several variations, including, many different constructive techniques, shapes and decorations that were not standardized. Every building is the final result of different influences and combinations in order to solve practical problems, as well as further additions and changes over time (Maietti et al., 2017). For this reason, aiming at the standardization in heritage documentation data handling and management, the Inception project is developing common parameters, setting a nomenclature or "glossary of names" as a starting point to semantic enrichment and modelling in BIM environment (Logothetis et al., 2015). The recognition of shapes, either manually or automatically performed, is possible only if single architectural elements (or their variations) are identified and univocally classified following a shared procedure (Maietti et al., 2018b).

Standardization of data can be done using the ifcOWL (Niknam and Karshenas, 2017). It is a standard IFC file (Pauwels and Van Deursen, 2012) used to pass information between different software or BIM environments, written in STEP or XML language based on a predefined schema. For example the buildingsmart consortium[26] structures the information within the models according to the logic: "there is an object called wall within which there are 3 sequential measurements that are height, length, thickness". The owner of the scheme is able to read an IFC file. ifcOWL is an IFC translation system, starting from the schema, in semantic language which consists of semantic triplets. Most important, these semantic triplets are written to be read by both machines and humans and are structured in subject, predicate and complement. (S) wall (P) has length (C) 10 meters. Subject and complement, or simply object, come from the IFC file and the predicate from the schema. The predicate definition in semantic language is called ontology (Tibaut et al., 2018). If one uses ontology, there is no longer a need for a scheme to read the ifc. Consequently, if in the ifc file there are properties not foreseen by the schema (and therefore by the ifcOWL) it is possible to elaborate a new ontology. Ontology can be defined as: a formal representation of knowledge as a hierarchy of concepts within the Cultural Heritage domain. The linguistic definitions related to the ontology concepts can also be used as shared vocabulary to denote the types, properties and interrelationships of Cultural Heritage aspects (Achille et al., 2016). The Inception Project creates the semantic system BIM for Cultural Heritage. It has created its own ontology, referring to the definitions of different vocabularies (in particular those of the Getty Institute,[27] that include terminologies for art, architecture, decorative arts, archival materials, and visual surrogates)[28] already structured in a standard way and designed

26 BuildingSMART: https://www.buildingsmart.org/.

27 The Getty Institute: https://www.getty.edu/conservation/our_projects/current.html.

28 Getty Vocabularies: https://www.getty.edu/research/tools/vocabularies/Linked_Data_Getty_Vocabularies.pdf. See also: https://www.getty.edu/research/tools/vocabularies/aat/about.html.



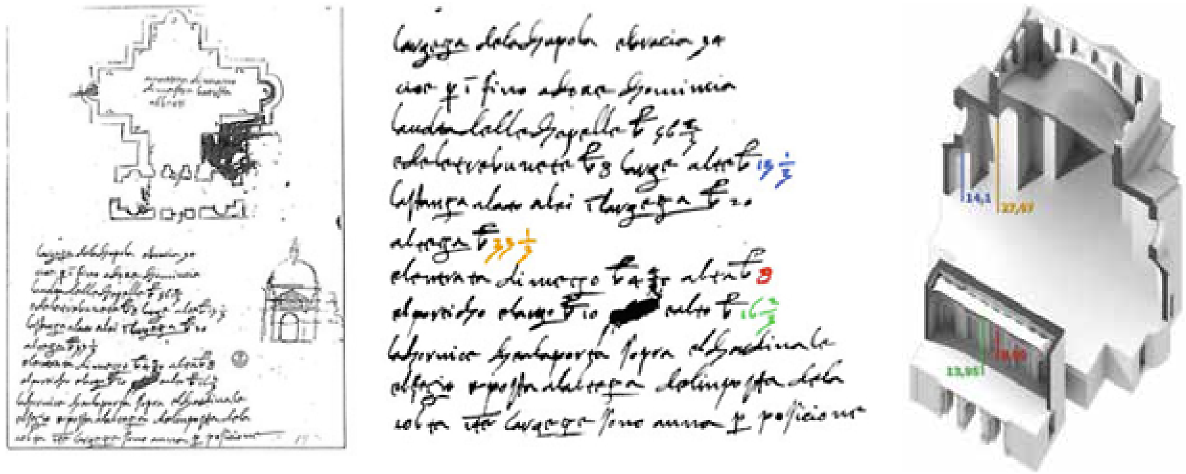


Fig. 4.2 "Media objects" of the Renaissance, were based on text and to a limited extent on images. Source: Palladio, A., 2002. *The four books on architecture*. Mit Press.

Fig. 4.3 San Sebastiano church in Mantua, by Leon Battista Alberti. The BIM model obtained from the point cloud is used as graphical verification of measures starting from the drawing by Antonio Labacco, beginning of the sixteenth century. Source: 2015 DIAPReM, DA-Unife, published in Maietti, F., Di Giulio, R., Balzani, M., Piaia, E., Medici, M. and Ferrari, F., 2017. Digital memory and integrated data capturing: innovations for an inclusive cultural heritage in Europe through 3D semantic modelling. In *Mixed reality and gamification for Cultural Heritage*. Springer, Cham. pp. 225-244 to integrate information open access[29] to what is called a semantic web (Benjamins et al., 2004). These vocabularies provide an extensive list of object terms in different thematic areas and relate each object term to others within a hierarchical taxonomy (Fig. 4.4). Due to the fact that the needs of each institution are diverse, some of these standardized vocabularies provide controlled flexibility, by allowing the specialized user to add new terms within the vocabulary, in order to express finer points of distinction among similar but subtly different objects (Bonsma et al., 2016a). For the definitions that integrate the BIM models (Fig. 4.5), the Inception Project developed a simple ontology that only one predicate results in the words "has definition Getty". (S) wall (P) has definition Getty (C) cavity wall. The complement comes from the Getty dictionary which eventually explains what the cavity wall is with other triplets.

The Inception Project used as a demonstration case (Maietti et al., 2018a) the Istituto degli Innocenti in Florence, an example of Italian Renaissance architecture, for which they were aggregated semantic attributes to the 3D geometric model. The semantic part consisted of nomenclature and interpretation of the building elements, integration of additional documents related to the history of the building and information related to the 3D data capturing, as a support for possible future maintenance or restoration works. The three-dimensional data captured in the form of point cloud and the massive variety of significances that are represented by the building, were aggregated into a BIM environment, where the building elements were classified following the IFC standard (Iadanza et al., 2019). In addition, the Getty Vocabularies were used to associate the elements of the model with semantic information. The procedure consisted of:

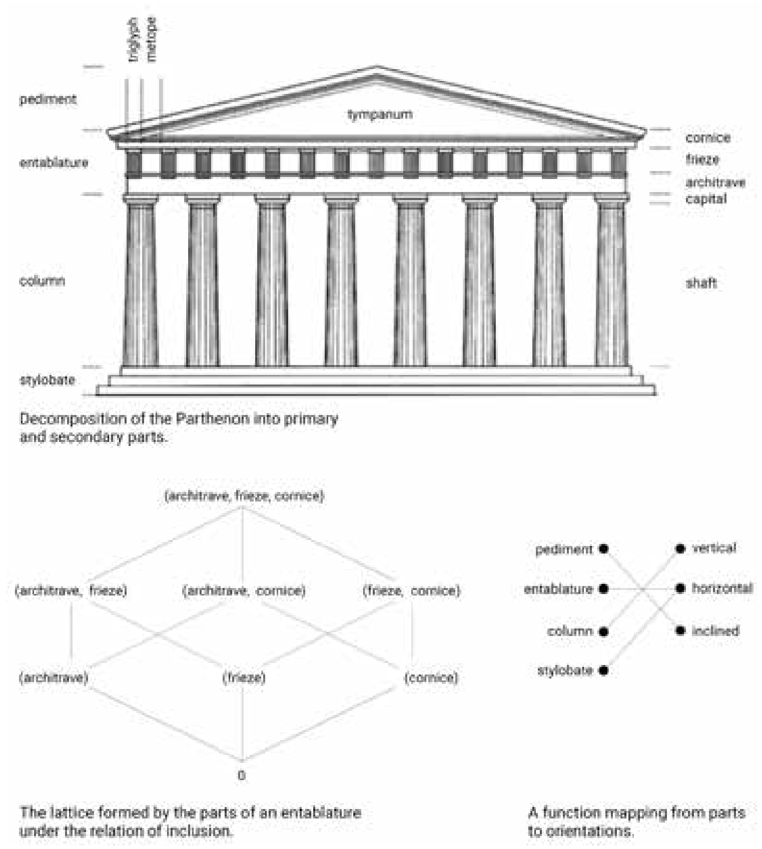
- translate the vocabularies/thesauri in a technology that supports linked open data;
- interlink the different vocabularies/thesauri and link them together;
- filter what is relevant for the H-BIM ontology within Inception.

The outcome of this procedure was disseminated through the development of an open-standard Semantic Web platform.[30] It interlinks the platform with external Cultural Heritage available linked data and makes it gradually enhanced by further ontologies. In fact, switching from a traditional BIM model to H-BIM is a matter of knowledge and how to aggregate it to a 3D model.[31] The development of the Inception platform took into account the concept of “circular workflow”. The use and re-use of 3D models, and related semantically aggregated data, is the starting point for the development of connected external applications. Currently, the latest developments in the VR/AR field are even more frequently matching the needs of the construction sector and changing the way construction professionals and designers do business with customers and with each other (Iadanza et al., 2019). The way to align the various data forms is through BIM technology and, thanks to its implementation within the Inception project, it is now possible to exploit those potentialities also for the Cultural Heritage field.

29 The Linked Open Data Lod Cloud: https://lod-cloud.net/.

30 The Inception semantic platform: http://www.inceptionhbim.eu/Platform/.

31 Istituto Innocenti within Inception Platform: http://www.inceptionhbim.eu/Platform/.



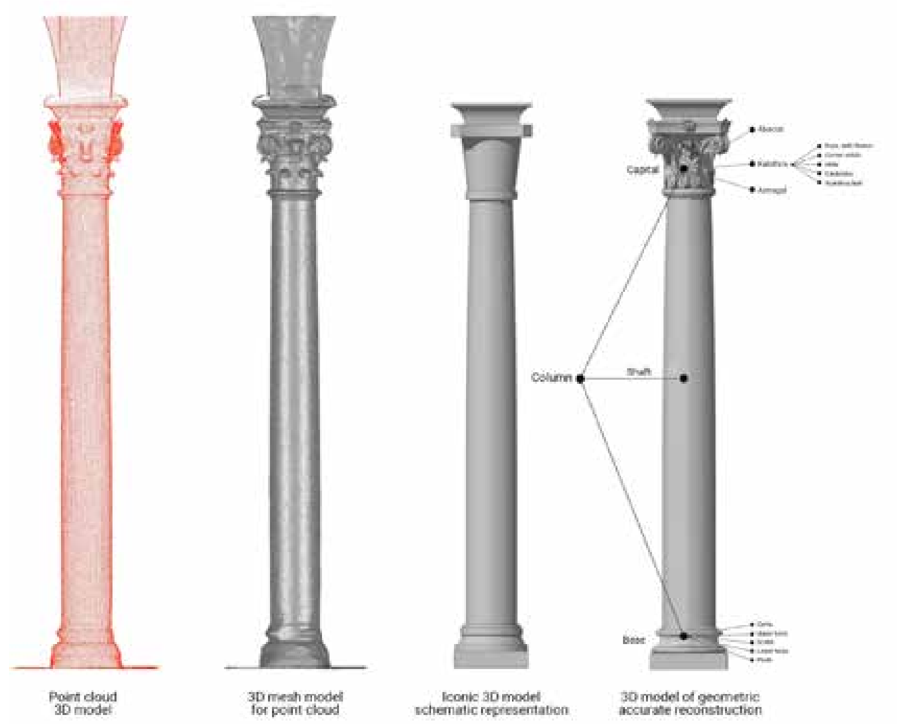


Fig. 4.4 Hierarchical terms to describe Cultural Heritage. Example of “storage of values and properties” in data structure through the decomposition of the Perthenon into parts. Source: Mitchell, W.J., 1990. *The logic of architecture: Design, computation, and cognition*. MIT press.

Fig. 4.5 Transition from digital documentation to semantic modeling. Source: Inception deliverable 5.3, Italian Demonstration Case. User-oriented Applications and Validation Result. Available at: https://ec.europa.eu/research/participants/documents/.

Data interoperability (Maietti et al., 2018b) suggests the possibility of using discrete data forms to create a coherent model capable of generating predictive models of the progression of degradation in buildings. In this way it is possible to hypothesize the integration of semantic models with algorithms representative of intervention logic on degradations through automated tools. In fact, the history of the interventions could be cataloged not only with the volumes of the new interventions but also with the robotic toolpaths that defined them, according to additive or subtractive procedures, whose logics can be replicated with the use of different materials or sub- architectural systems. The use of digital fabrication in recovery processes is an opportunity to manage entire digital workflows, in a continuum (Leach, 2002) that goes from planning to realization. Workflows generate data that can be used to inform models and processes. The open source upload of information relating to the manufacture, tools and performance of materials for restoration or emergency interventions constitute a broad area of investigation that can be opened in the near future.

4.3.3 Europeana: digitizing European Cultural Heritage

The Inception Project represents the systematization of the results and approaches of various European research projects that have been undertaken since 2005, the year in which the first guidelines for digital storage of tangible assets was defined.[32] Since 2005, the European commission has cataloged the "timeline of digitization and online accessibility of Cultural Heritage",[33] which contains numerous significant passages. One of these passages is the development, in 2006, of the first European digital library,[34] initially defined as an experiment by the National Library of France and then spread to other Member States. The project was part of the 2010 program, which "set out its strategy for digitisation, online accessibility, and digital preservation of Europe's collective memory through a pan-European working group".[35] The spread of the platform and the growth of a multilingual database defined the priority of developing a roadmap for a cross-domain portal.

In 2006, the council of the European union proposes to extend the digitization approach to scientific information through "Communication from the Commission to the European Parliament on scientific information in the Digital Age".[36] In the document, in the section "the importance of scientific information" it includes: "in order to become an increasingly competitive knowledge-based economy, Europe must improve the production of knowledge through research, its dissemination through education, and its application through innovation. All research builds on former work, and depends on scientists' possibilities to access and share scientific publications and research data". In the same year the Council formally invited Member States to "work together at European level on the

32 Tangible Heritage: http://www.unesco.org/new/en/cairo/culture/tangible-cultural-heritage/.
33 Timeline of digitization and online accessibility of Cultural Heritage: https://ec.europa.eu/digital-single-market/en/news/timeline-digitisation-and-online-accessibility-cultural-heritage.
34 Commission recommendation on the digitization and online accessibility of cultural material and digital preservation: https://eur-lex.europa.eu/legal-content/.
35 Commission Recommendation of 24 August 2006 on the digitisation and online accessibility of cultural material and digital preservation: https://eu.vlex.com/vid/digitisation-accessibility-preservation-36414775.
36 Communication on scientific information in the digital age: https://eur-lex.europa.eu/legal-content/.

accessibility and preservation of scientific information" with the document *Council Conclusions on Scientific Information in the Digital Age: Access, Dissemination and Preservation* in which it is noted that "access to and dissemination of scientific information – publications and data – are crucial for the development of the European Research Area, and can help accelerate innovation".

In 2008, the Europeana portal was launched,[37] a common multilingual access point to Europe's Cultural Heritage online, with the aim of creating an interoperable infrastructure and a cross-border network for digital Cultural Heritage.[38] The main purpose of this initiative lies in driving an innovative, smart, sustainable and inclusive European growth.[39] At the operational level, the category of users identified for the operation of the platform consists of general users, school students, academic users (undergraduates, postgraduates and teachers), expert researchers, professional users such as librarians, archivists, and curators (Purday, 2009). From the same users, "the digitised material from cultural institutions can be re-used to develop learning and educational content, documentaries, tourism applications, games, animations, and design tools".[40] At the time of writing, Europeana gives direct access to more than 19 million digitised objects.

Before the refinement implementation by the Inception project, the Europeana platform directed semantic web research into digital archive operations. In 2011, a commission promulgated "Recommendation on the digitization and online accessibility of cultural material and digital preservation",[41] in which there is a section with the key points for the future implementation of Europeana by Member States are suggested, through:

- ensuring the use of common digitisation standards defined by Europeana in collaboration with the cultural institutions in order to achieve interoperability of the digitised material at European level, as well as the systematic use of permanent identifiers;
- ensuring the wide and free availability of existing metadata (descriptions of digital objects) produced by cultural institutions, for reuse through services such as Europeana and for innovative applications;
- establishing a communication plan to raise awareness of Europeana among the general public and notably in schools, in collaboration with the cultural institutions contributing content to the site.

37 Europeana portal: https://www.europeana.eu/portal/en. It currently provides more than 26 million boks, paintings, films, recordings, photographs, and archive material from over 2.200 partner institutions including museums, libraries, and archives.
38 Council conclusion of 20 November 2008 on the European digital library EUROPEANA (2008/C319/07): https://eur-lex.europa.eu/legal-content/.
39 Europeana - a European Cultural Heritage platform for all: https://ec.europa.eu/digital-single-market/en/europeana-european-digital-library-all.
40 Timeline of digitisation and online accessibility of Cultural Heritage: https://ec.europa.eu/digital-single-market/en/news/timeline-digitisation-and-online-accessibility-cultural-heritage.
41 Recommendation on the digitization and online accessibility of cultural material and digital preservation (2011/711/EU): https://eur-lex.europa.eu/LexUriServ/.

The definition of the semantic aspect of the platform, called Europeana Semantic Elements (ESE)[42] was developed through the Europeana Pro system,[43] a project presented at the Dublin Core[44] 2011 conference. It was described as "a methodology of making Europeana metadata available as Linked Open Data on the Web. It allowed others to access metadata collected from Europeana data providers via standard Web technologies. The data represented in the Europeana Data Model (EDM). Links between Europeana resources and other resources in the Linked Data Web[45] which enabled the discovery of semantically related resources" (Haslhofer and Isaac, 2011).

Europeana's approach has encouraged research on heritage classification methodologies. The project EU-CHIC,[46] European Cultural Heritage Identity Card[47] for example, focuses on architectural and archaeological heritage by defining a documentation protocol. It highlights which buildings are at risk and which are damaged, in order to plan preservation, conservation and restoration. The basic idea is to "facilitate the increase of knowledge on the heritage building stock across Europe to support the development of sustainable maintenance, preservation, and the revitalization of historic sites and monuments" (Žarnic and Vodopivec, 2012).[48] Among the outcomes of Europeana is the dissemination of information concerning the assets at risk, such as the collection of historical documents "Heritage at risk. Protecting and preserving endangered Cultural Heritage",[49] where loss or damage to important buildings due to natural disasters, socio-political tensions, or human

42 Europeana Semantic Elements (ESE) documentation: https://pro.europeana.eu/page/ese-documentation.
43 Europeana Pro: https://pro.europeana.eu/page/linked-open-data. It an experimental pilot in February 2012 with a small number of data providers who committed at an early stage to Europeana's initiative of promoting more open data. In October 2012, a large subset of the Europeana's dataset (metadata on 20 million texts, images, videos and sounds) was transformed into linked data and made available online.
44 Dublin Core Metadata initiative: https://www.dublincore.org/specifications/dublin-core/dcmi-terms/.
45 DCMI International Conference on Dublin Core and Metadata Applications: https://dcpapers.dublincore.org/index.php/pubs/article/view/3625.
46 EU-CHIC is funded under the FP7-Environment programme, from 2009 to 2012. See Cordis fact sheet: https://cordis.europa.eu/project/rcn/92042/factsheet/en.
47 EU-CHIC: http://www.euchic.eu/.
48 The classification of heritage assets can be described as follows: A) Architectonic assets with two main bearing structural elements: vertical walls and horizontal floors (palaces, castles); B) Architectonic assets characterized by wide spaces without intermediate floors and few inner walls (churches, mosques); C) Architectonic assets in which the vertical dimension prevails on the other ones (towers, minarets); D) Architectonic assets in which the main structural element is an arch or a vault (triumphal arches, bridges); E) Massive constructions in which the wide thickness of walls, if compared to other dimensions, doesn't allow the idealization as plane structural element (fortresses, ramparts); F) Single, isolated architectonic assets, which does not delimit an interior space (columns, obelisks); G) Historical centers composed of ordinary buildings' aggregates, which assume the relevance of Cultural Heritage asset as whole in the urban context. Seismic response considers the interaction among adjacent buildings.
49 Heritage at Risk. Protecting and Preserving Endangered Cultural Heritage (section within Europeana portal): https://www.europeana.eu/portal/en/exhibitions/heritage-at-risk/icons-in-danger. Drawing on rich material from Europeana Collections, Heritage at Risk explores the natural and man-made threats to Cultural Heritage, from ancient times until today. It also examines the history of Notre-Dame and considers the role that digital technologies can play in the preservation and restoration of such fragile monuments.

activities are examined. Europeana is also a reference for several spin-offs, aimed at the digitalization of museum assets,[50] multimedia content,[51] and to the design of innovative archiving platforms.[52] The mass digitization that is intended to operate in the next European framework program, at the conclusion of H2020 will drive Europeana programme for the longer term.[53] The digitization of Cultural Heritage corresponds to the first step to insert the topic in a more complex ecosystem that gives rise to innovative design workflows. Europe's strategic actions in the field of cultural heritage are aimed at alignment with academic research and product innovation in the international framework. This dynamic will accelerate interest in emerging technologies.

4.3.4 The Time Machine Project: processing the big data of the past

In the context of Europe 2020,[54] the Time Machine Project[55] is distinguishing itself within the framework of FET Flagship Actions.[56] The FET (Future and Emerging Technologies) is a development program that invests in transformative frontier research and innovation with a high potential impact to benefit the economy and society.[57] FET Flagship is a subcategory of FET and is defined as visionary, large-scale, science-driven research initiatives that tackle grand scientific and technological challenges. In the other categories there are FET Open, which supports a bottom-up approach for exploring novel and visionary ideas and FET Proactive, which fosters transformative research through a set of focused thematic initiatives. Before entering the European circuits and involving other bodies in the research,[58] Time Machine established itself in the international scientific community through the project Venice Time Machine,[59] which is the product of a collaboration started in 2012 between the Ecole Polytechnique Federale de Lausanne (EPFL) and the Ca 'Foscari University of Venice. The work in progress consists of digitization of the historic archives of Venice in order to build a multidimensional 3D model of the city. The model can be used for research and education by creating a large, open, digital archive of the city's Cultural Heritage covering a period of more than 1000 years (Di Lenardo and Kaplan, 2015).

50 Athena Europe: http://www.athenaeurope.eu/.
51 European Film Gateway: http://www.europeanfilmgateway.eu/.
52 APEnet, Archives Portal Europe Network, http://www.apenet.eu/. Its objective is to build an Internet Gateway for Documents and Archives in Europe where seventeen European National Archives in close cooperation with the Europeana initiative were to create a common access point to European archival descriptions and digital collections.
53 See the documents "Evaluation of Europeana and orientations for its future development" and "Report from the Commission to the European Parliament and the Council Evaluation of Europeana and the way forward". 1) https://publications.europa.eu/en/publication-detail/-/publication/58538a59-b4aa-11e8-99ee-01aa75ed71a1/language-en; 2) https://eur-lex.europa.eu/legal-content/EN/ALL/?uri= COM:2018:0612:FIN.
54 Cordis fact sheet for Time Machine: https://cordis.europa.eu/project/rcn/221493/factsheet/en.
55 Time Machine project: https://www.timemachine.eu/. It is funded under: H2020-EU. 1.2.3.
56 FET flegships actions: https://ec.europa.eu/digital-single-market/node/10630.
57 FET programme: https://ec.europa.eu/digital-single-market/en/policies/future-and-emerging-technologies.
58 The Time Machine FET Flagship has three significant strategic partnerships with Europeana Foundation, Indra Sistemas S.A. and the French video game company Ubisoft, for the implementation of Time Machine's Large-Scale Historical Simulator, which will map 5000 years of European history.
59 Venice Time Machine project: https://vtm.epfl.ch/.

The project (Fig. 4.6) is based on a "mass digitization project of one of the largest archives in Venice, the Archivio di Stato",[60] which is estimated to contain 80km of shelves filled by administrative documents. Through the multidimensional model, researchers are reconstructing the history of Venice in 2D and 3D for any year starting from the origins of the city to present-day. The model is built using documents relating to economic transactions, population censuses, public works, circulation of news, commercial goods, migration, birth registrations, death certificates, tax statements, maps, urban planning designs, artistic patterns, and architectural patterns. The documents in the archive are entirely written by hand, in languages (predominantly written in Latin or the Venetian dialect) evolving from medieval times to the 20th century. The complexity of interpretation of the material is addressed through the use of a machine learning system. Text recognition algorithms have been developed to associate the shape of the letters (despite variations in fonts) and thus rendered searchable and cross-referenced through the large amount of documents.[61] The time machine algorithms are designed to analyse the structure of written text and pull out graphical shapes that look similar, forming a link between them. This was made possible by the contribution of the READ, Recognition and Enrichment of Archival Documents project.[62] For the survey of the most fragile manuscripts, mechanical arms were used to browse the pages in controlled environments or tomography scanners to read the contents without having to open the manuscripts. By combining the mass of information and turning handwritten documents into digital, searchable text, it is possible to reconstruct large segments of the city's past and open up reams of hidden history - complete biographies, political dynamics, or even the appearance of buildings and entire neighborhoods[63] (Kaplan, 2015). The Venice Time Machine can link citizens and businesses with historic maps of Venice, such as this sixteenth-century view of the city.[64]

The use of AI for historical research is allowing for the development of algorithms for the recognition of shapes on old drawings and to carry out transversal searches. This makes it possible to trace, for example, all the economic transactions in which a person who commissioned the construction of a work. A different example would be a search to select the designs in which there are buildings with pitched roofs. The information extracted from the primary sources are organized in a semantic graph of linked data and unfolded in space and time in a historic / geographic information system, creating the largest database ever created on Venetian documents. European collaboration has been effective in expanding Time Machine workflow (focused on 3D modeling, big data, AI, AR, and VR) to several European cities, including Amsterdam,[65] Budapest[66] and Parigi.[67] These collaborations encourage

60 Venice Time Machine : Recreating the density of the past: https://infoscience.epfl.ch/record/214895.
61 Europe Time Machine: https://www.arte.tv/en/videos/084799-001-A/europe-time-machine-1-5/.
62 Cordis READ: https://cordis.europa.eu/project/rcn/198756/factsheet/en.
63 From Frederic Kaplan TEDx talk in Geneva: https://www.youtube.com/watch?v=b6nfoE9ly90.
64 "The 'time machine' reconstructing ancient Venice's social networks. Machine-learning project will analyse 1,000 years of maps and manuscripts from the floating city's golden age", in *Nature* international journal: https://www.nature.com/news/the-time-machine-reconstructing-ancient-venice-s-social-networks-1.22147#/graphic.
65 Amsterdam Time Machine: https://amsterdamtimemachine.nl/.
66 Budapest Time Machine: https://hungaricana.hu/en/budapest-idogep/.
67 Paris Time Machine: https://www.timemachine.eu/timemachines/paris/.

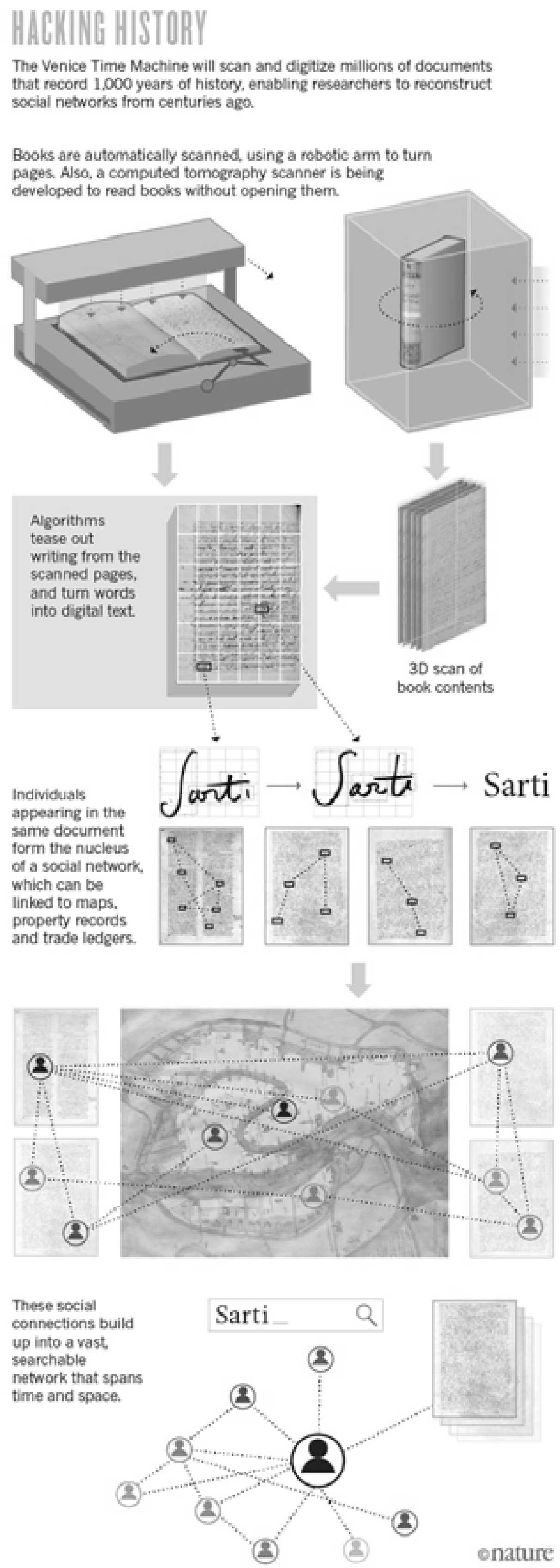


Fig. 4.6 The Time machine workflow. Source: Abbott, A., 2017. The 'time machine'reconstructing ancient Venice's social networks. *Nature News*, 546(7658), p.341.

the creation of a pan-European infrastructure[68] and digitalization of big data from the past (Fig. 4.7).[69] The interest of the project also turned to Cultural Heritage by referring, in its manifesto,[70] to the introductory text to the 2019 Declaration for the digitization of heritage with regard to the use of new technologies to prevent or intervene in situations of damage. Two partners from Time Machine, the start-up Iconem[71] and the French video game company Ubisoft, collaborated in the digitization and dissemination of the archaeological site of Palmyra, at the conclusion of the armed conflict on Syrian territory. The Iconem technicians carried out a geometric survey on the post-destruction site (differently from the IDA that carried out a pre-destruction survey) with the help of drones for the collection of photogrammetric information.

The data collected were processed by Ubisoft to elaborate the three-dimensional model and the reconstruction of Palmyra in VR, so that it can at least continue to exist virtually. The resulting work was exhibited at the Arab World Institute in Paris to disseminate knowledge of operational methodologies for the protection of international as well as European assets. In the description of the exhibition Age Old Cities it states "the aim of the exhibition is to immerse the public in the splendors of these major centers of world heritage, but also to raise awareness about the stakes involved in preserving and protecting these precious and fragile riches".[72]

The examples above are relevant to the European collective culture because of their ambitious scale and the new technologies that are under development: from state-of-the-art scanners that could read unopened books, to the VR reconstruction of architectural losses, to adaptable algorithms that will turn handwritten documents into digital, searchable text. The fulfillment of the Time Machine project will pave the way for more ambitious projects within the realm of the so called Digital Humanities.[73]

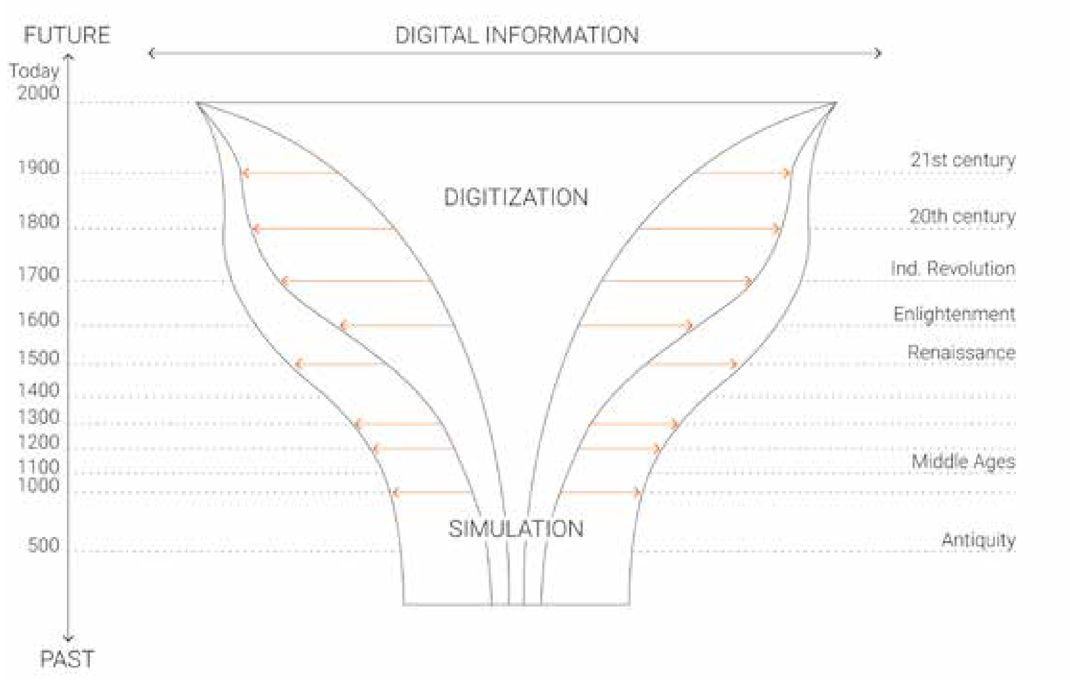


Fig. 4.7 The Information Funnel: the more the curve goes down, back in time, the more it shrinks. In order to create a past as dense as a present, digitization and extrapolation of data (simulation) are needed. Source: "The Venice Time Machine", Frederic Kaplan speech at TEDxLakeGeneva: https://www.youtube.com/watch?v=b6nfoE9ly90.

68 Time Machine infrastructure for digitising and processing Cultural Heritage: https://www.timemachine.eu/time-machine-a-pan-european-digitisation-and-processing-infrastructure/.

69 From Frederic Kaplan lecture at the World.Minds Annual Symposium 2017: https://www.youtube.com/watch?v=6brInBZ-jLk.

70 Time Machine manifesto: https://documents.icar-us.eu/documents/2019/05/time-machine-manifesto.pdf.

71 Iconem start-up: http://iconem.com/en/.

72 Age Old Cities exhibition: https://www.imarabe.org/en/exhibitions/age-old-cities.

73 European Association for Digital Humanities: https://eadh.org/projects.

4.4 Digital approach to Architectural Heritage

"One day I visited the site during the erection of the prefabricated frame of the building [...] Now I'm glad of this experience because it made me aware of the meaning of the crane in design, for it is merely the extension of the arm like a hammer. Now I began to think of members 100 tons in weight lifted by bigger cranes [Louis Kahn, 1960]

The methods and processes for the implementation of conservative strategies of the architectural heritage have developed over the years through both linguistic and expressive theories. The multiple dialogues between the different cultural matrices of the debate within the scientific community have expressed different ways and times to address the planning and intervention actions. These actions evolve according to the guidelines of protection and valorization matured in different historical moments. However, in terms of implementation procedures, there is a firm crystallization of processes still closely related to craftsmanship. It is difficult to identify innovative alternative solutions capable of upgrading approaches to the preservation of Cultural Heritage. The execution of restoration projects rely on a case by case method and are always conceptually unavoidable. Unfortunately the case by case model remains deficient in more advanced processes that can provide greater precision, repeatability, predictability, assurance of results, measurability of performance in the process of recovery, and enhancement of Cultural Heritage.

Using terminologies typical of other categories of innovation developed in the European context, especially in the seventies, are oriented to the large-scale construction of new contemporary building through the production of standard elements. The introduction of some principles of industrialization in the recovery processes can be hypothesized. With a critical approach, this introduction of innovative methods can find space within the conservative push, without being associated with a necessarily serial production and therefore incompatible with historical buildings. The practices that take into consideration the use of new tools can be integrated with the artisan customs currently present on the site of conservation of monuments or buildings.

The off-site production of materials, products, and technologies (from mortars and premixed plasters, to doors and windows) is a process already established on the recovery site, which is bringing about a higher quality control and certified performance. Other levels of process innovation could be improved through the prefabrication of components and therefore in a protected environment, suitable to raise the quality of the result. These innovative approaches might not rely on large-scale replicability, but on perfect execution for both discretized and similar elements Examples might include a cornice or for technological units such as an entire portal.

The possibility of making digital survey systems with industrial robots customizable according to specific project needs could play a significant role in changing the nature of the restoration site. The flexible nature of robots makes it possible to carry out work that can be subtractive, additive, or for the installation of components through pick and place routines. This technical possibility responds to the range of needs required by the recovery processes of the existing site which, more than in other construction contexts, require that certain decision and operative phases are carried out directly and immediately on-site.

Innovation in construction has often started thanks to technology transfer from other contexts, including naval engineering and aeronautics. New materials, technologies, and processes belonging mainly to industrial production can open up new scenarios for the recovery of existing buildings, both for preventive protection and for post-emergency situations.

Starting from the scale of the object, there have been several experiments involving the use of digital fabrication for the reproduction or conservation of cultural assets, mainly for museum purposes. The interest in the field coincided with the spread of additive and subtractive production tools, which have stimulated research in the sector to understand its limits and potential. These tests were fundamental in advancing the state of the art of knowledge to assess the scalability of processes to the dimension of unit or the architectural technological system.

In 2007, a multidisciplinary group of Italian researchers[74] collaborated with a German research center for the reproduction of the head of Maecenas, a marble work preserved in the National Archaeological Museum of Arezzo. The copy of the object was made using a robot programmed to perform subtractive processing by carving a block of material (Fig. 4.8). This process is more commonly known as a computer-controlled milling tool (CNC machinery). The project made a physical copy of an existing artifact to verify the maximum level of accuracy achievable and consequently understand the domain of application. The choice of the subject to be reproduced was related to the geometry of the statue that required a precise robotic toolpath. Every point of the carved surface was properly analyzed and associated with a plane whose normal represents the direction in which the milling tool affects the material. The choice of technology was predicated on the adaptability of the process to operate with a wide range of materials, from wood to stone to metal. The three-dimensional model used to guide the milling robot was based upon a digital three-dimensional survey performed with laser triangulation on the original work. The subtractive milling process took place in different phases, each of which was performed by progressively reducing the size of the cutting tool to get greater and greater detail. The large working space that was defined by the movement of the six axes of the robot did not constitute technical complexity for achieving the result. The remaining unresolved limits of the tool were only able to be completed with manual intervention for finishing details and for cleaning the product. A very detailed 3D reproduction of the original artwork was obtained, which completely fulfilled the expectations of the museum.

Digital fabrication technologies can also contribute to Cultural Heritage restoration methodologies. Many artworks are discovered with important missing parts. In 2009 a team of researchers[75]

74 Il Ministero dell'Istruzione e della Ricerca tedesco ha commissionato al CNR – Istituto di Scienza e Tecnologie dell'Informazione di Pisa e al Gruppo Scienzia Machinale, www.grupposcienziamachinale.com, la riproduzione della testa di Mecenate, nell'ambito del programma di ricerca "Maecenas".

75 The restoration project was carried out under the coordination of the Superintendency for Historical, Artistic,

decided to use additive digital fabrication technology for the recovery of a highly damaged historical-cultural asset (Arbace et al., 2013). The Madonna of Pietranico, a terracotta statue whose volumetric configuration was lost following the earthquake that struck Abruzzo in 2009 was used in this project. The recovery process started with the three-dimensional scanning of the fragments and with the processing of the spatial data necessary to identify the relative position (Fig. 4.9). It was decided to use additive manufacturing, a technology identified on the basis of the need to carry out a precise, resistant, low-cost and complex geometry intervention, to create a support structure to integrate the lost fragments of the statue. The recombination of the fragments was not possible by simply gluing them back together, due to the eroded fracture surfaces and the missing components.

The comparison with the historical images available allowed a double confirmation of the accuracy of the support volume to be prototyped, for which numerous assembly tests were defined with the authentic elements of the work. The 3D modeling phase of the statue's volume with the filling support had to take into consideration the irregular dimensions of the fragments and at the same time the need to develop a non-invasive and reversible intervention. It was decided to use a 3D printer equipped with nozzles programmed to deposit layers of gypsum and synthetic binder to define a support volume for the light and resistant work, suitable for collaborating with a terracotta work, which has brought back the legibility of the statue in its overall image.

As summarized in the review “Digital Fabrication Techniques for Cultural Heritage” (Scopigno et al., 2017), the reproduction of low-scale architectural models for museums can take advantage of digital fabrication techniques to allow novel interaction paradigms (Grellert and Pfarr-Harfst, 2013), such as:

- replication of work for people with disabilities who can access the heritage through tactile experiences;
- temporary or permanent replacement of works from their original location which, for example, must be subject to restoration work;
- tailored packaging processing or support structures for storage, shipping or displaying fragile CH artworks, for example through rapid prototyping of reticular structures. For these purposes, the research is in progress for the multi-material printing, so the support structures can be softer at the contact surfaces with the works;
- definition of sensorized copies to transform them into active replicas, for example to facilitate richer interactions in museum installation;
- replication of work for educational purposes to make digital catalogs tangible. The Smithsonian museum[76] in fact it has a large multimedia catalog of its collections, enriched with interactive semantic information. The complete experience of the most important works can be made through a physical reproduction of the object with which it is possible to interact.

Artistic and Ethno-anthropological Heritage of L'Aquila, with the collaboration of CNR-ISTI Visual Computing Lab (Pisa), Tryeco 2.0 s.r.l. (Ferrara), Equilibrarte s.r.l. (Rome).

76 Smithsonian museum 3D models catalogue: https://3d.si.edu/.

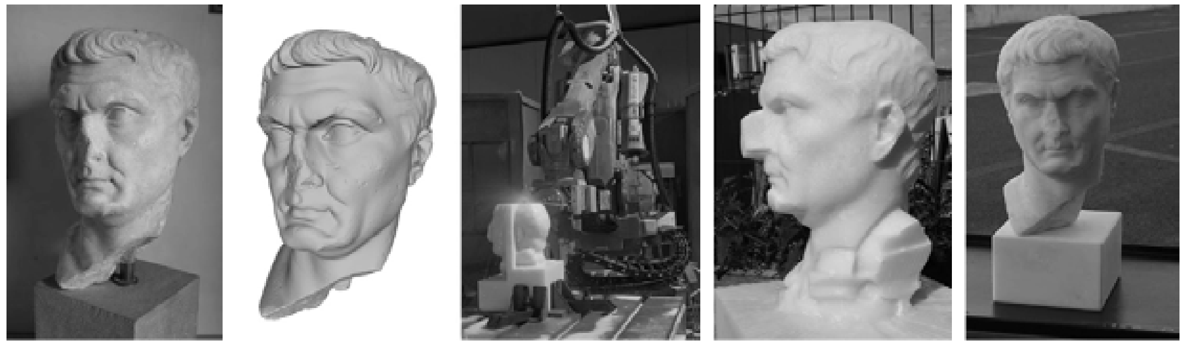


Fig. 4.8 Process of reproduction of the Head of Maecenas by subtractive technique. Source: Scopigno, R., Cignoni, P., Pietroni, N., Callieri, M. and Dellepiane, M., 2017, January. Digital fabrication techniques for cultural heritage: A survey (p.7). In *Computer Graphics Forum*. Vol. 36, No. 1.

Fig. 4.9 Digital reconstruction of the Madonna di Pietranico. Source: ivi. p.15. *Computer Graphics Forum.*

There are numerous application examples of using these technologies. Digital fabrication techniques were also used to create full size replicas fragments and for assembly testing for the restoration of Tullio Lombardo's Adam (Riccardelli et al., 2014). Another example of full-scale reproduction is the portion of a Pompeii wall covered in inscriptions, produced for a temporary exhibition for the Salone del Restauro in Ferrara.[77] This work was a collaboration involving Diaprem[78] and CNR-ISTI.[79] The aim was to produce a high-quality replica, enhancing the Latin inscriptions with colours in order to increase their readability. To reduce the reproduction cost and weight, a 3D additive printing machine (glued gypsum powder) was used. The large model (270 × 330 cm) was divided into 125 tiles, each one printed on a ZCorp 3D printer. All these pieces were mounted using a supporting structure (Balzani et al., 2004). The scalability of processes is of interest in the academic research sector, where the association between digital fabrication and heritage has been taken into consideration for experiments in the laboratory environment. In the context of the *Rob | Arch 2014* conference, the Variable Carving Volume Casting project (Fig. 4.10) was presented, which expresses a method for rapidly carving variable molds to cast unique volumetric elements, without material waste. EPS foam is the carved material. This method employs a multi-axis robotic arm with a hot-knife to carve foam into mass-customized negatives, which deviate from the aggregation of standard building components. Beyond the result, which consists of prototypes of freeform columns in glass fiber reinforced gypsum cast in the negatives obtained with robotic procedure, it is interesting to read the approach of the researchers in the introduction to the experimentation.

In reference to Ruskin's theories expressed in the text The nature of Gothic, the production of architectural units is determined by the maker and his methods of making, unlike the classical approach whereby the forms are predominantly determined by the thinker. In a neo-ruskianism perspective, designers tend to occupy the place that inspired their hands (digitally augmented hands). The use of digital manufacturing technologies means that the architect acquires control of the entire design process, from the formal generation to the construction, from virtual to physical space. Process control emerges in the creation of a digital model capable of incorporating the parameters relating to materials, geometric constraints and the tools used, defining a new relationship between designer and maker (Sheil, 2012). The use of digital fabrication in this experimental context is carried out to find a "harmonious relationship" between the two instances since "robotics are translating craft traditions into a digital environment full of feedback and variability" (Clifford et al., 2014).

The examples reported so far highlight a growing attention of the research sector towards the definition of a cultural paradigm that links manufacturing and technology. This approach is worthy of further study in the context of the recovery site. The following paragraphs describe digital fabrication projects that have addressed the architectural scale. The first significant case is the continuation of the

77 Salone del Restauro in Ferrara: https://www.salonedelrestauro.com/.
78 Diaprem Unife: http://www.diaprem.unife.it/diaprem-1.
79 CNR-ISTI: https://www.isti.cnr.it/.

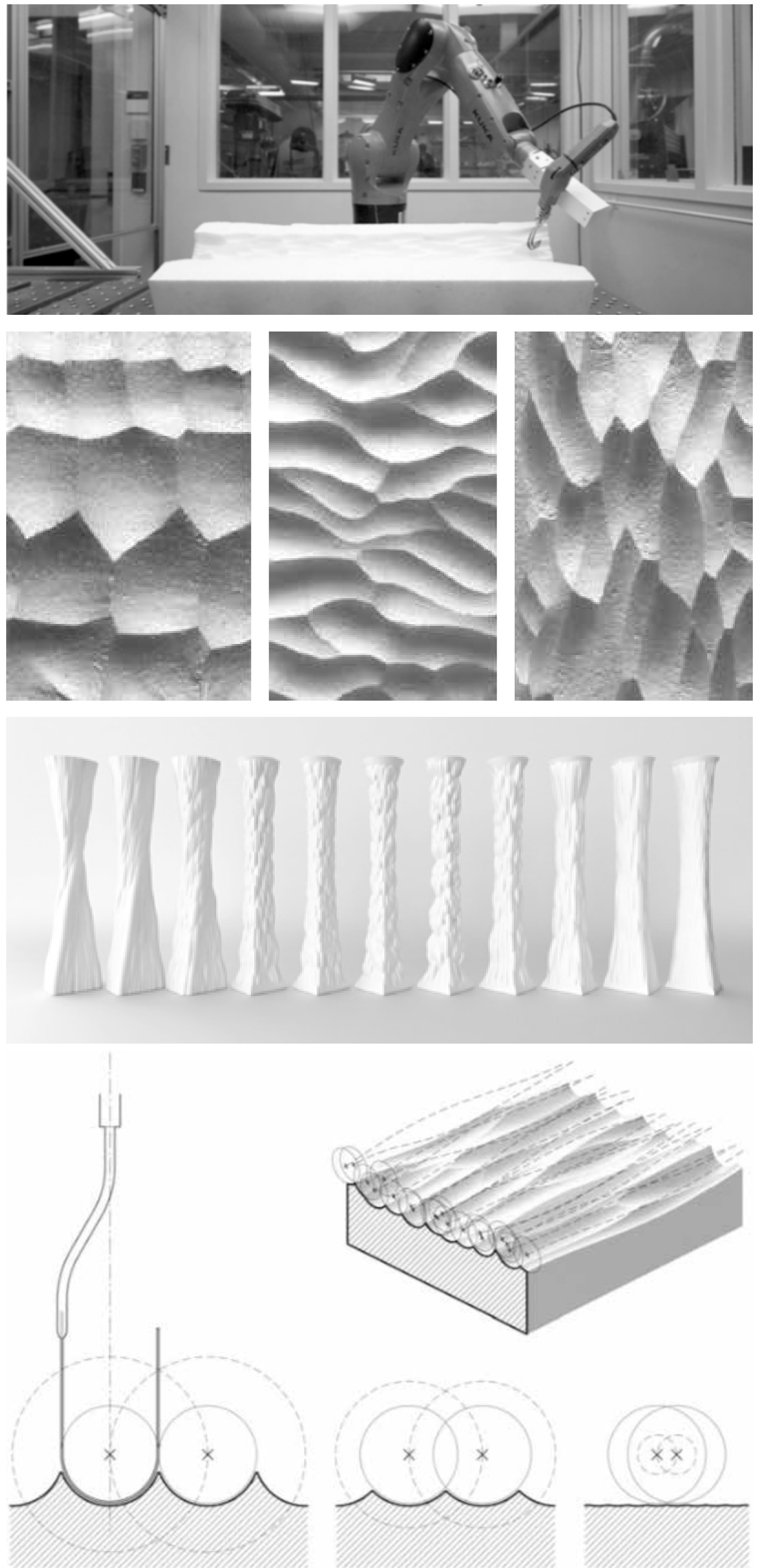


Fig. 4.10 The project Digital Gothic, the use of robotics for speculations on geometric reconstruction of historical geometric languages. Clifford, B., Ekmekjian, N., Little, P. and Manto, A., 2014. Variable carving volume casting. In Robotic Fabrication in Architecture, Art and Design 2014. Springer, Cham. pp. 3-15.

construction of the Sagrada Familia Church in Barcelona through the use of robotic technologies.[80] The second example is the reproduction by subtractive methodology of the Palmyra arch[81] in an emergency situation of non-accessibility of the reconstruction site. The interest is directed towards the approach in the comparison of the use of these technologies and to the development of a critical thought that allows the application of a new paradigm of digital craft, that is in continuity with the workers who produced the historic buildings. Given the speed with which these technologies are evolving and becoming accessible, it is necessary to define a theoretical position on the subject before the technique prevails over the conservative debate.

4.4.1 Robots at the Sagrada Familia: digital Gaudi

The continual construction of the Sagrada Familia Church in Barcelona is an example of how computational design workflows and the production of complex geometries has evolved over more than two decades, advancing the volumetric integration of an architectural pre-existence. The opportunity to see technical innovation documented so thoroughly on a single testbed is the result of the contingent conditions that characterize it. Due to the size and complexity of the building elements, the construction phase of the Sagrada Familia, still in progress, requires the programming of human, technical, and economic long-term resources. The work of the professionals involved is evidence of the optimization of processes and the application of high technology to geometrically define and carve massive stone elements to complete the formal unity of a high historical value artifact.

Mark Burry[82] has published extensively on this topic, as he is the architect in charge of managing the progress of construction, holding the role of executive architect and academic researcher. From the nineties to the present day, Burry has disseminated the state of the art in terms of both design and production of construction units. This dissemination is based on photographs of the study models, surviving fragments of plaster models developed by Gaudi, or drawings not yet defined for the architectural-executive practice. Gaudi approached the construction of the Sagrada Familia as Brunelleschi had done for the dome of Santa Maria del Fiore, that is without executive drawings but "supervising all in person, as an artisan / author who explains living voice or shapes with his hands what he has in mind "(Carpo, 2011). Gaudi built without notations. He wanted to express a revival of the medieval way of building, to find an idea of order and social organization in the context of the industrial Barcelona.

In 1996, with the paper "Parametric design and the Sagrada Familia", Burry explained that for the digital control of complex shapes such as second order (doubly ruled) surfaces and for the quality of the result, one had to resort to the most advanced computational techniques available, or those that

80 The Sagrada Familia, a pioneer in applying manufacturing robots to architecture: https://blog.sagradafamilia.org/en/specialists/applying-manufacturing-robots-to-architecture/.

81 Digitally reconstructing the faces of ancient palmyra: https://www.forbes.com/sites/drsarahbond/2017/07/05/digitally-reconstructing-the-faces-of-ancient-palmyra/.

82 Mark Burry: https://iaac.net/dt-team/mark-burry/.

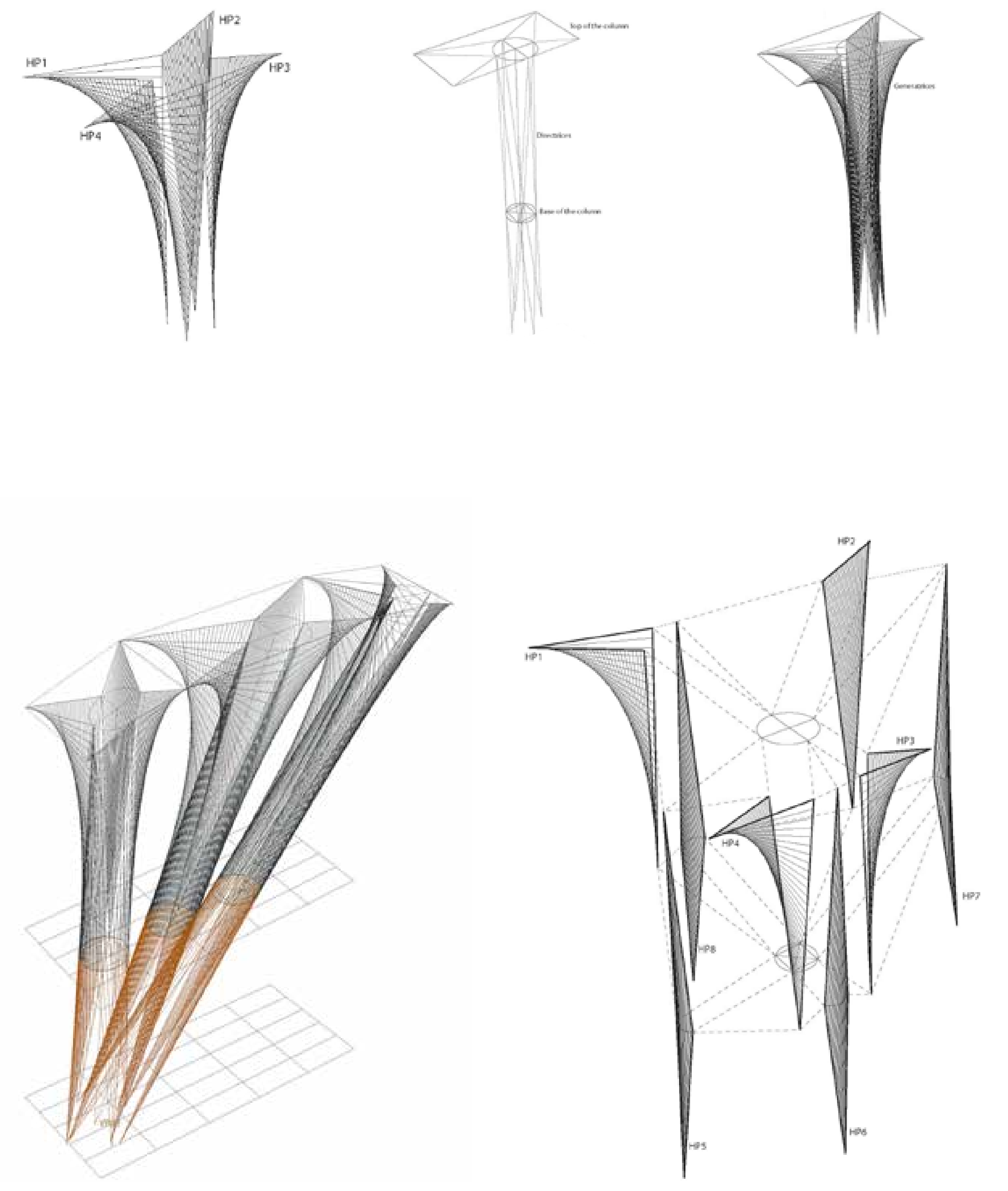


Fig. 4.11 Parametric 3D model of a column of the triforium in the Sagrada Familia church, based on the assembly of hyperbolic paraboloids. Source: Burry, M., 1996. Parametric design and the Sagrada Familia. *arq: Architectural Research Quarterly*, 1(4), pp.70-81.

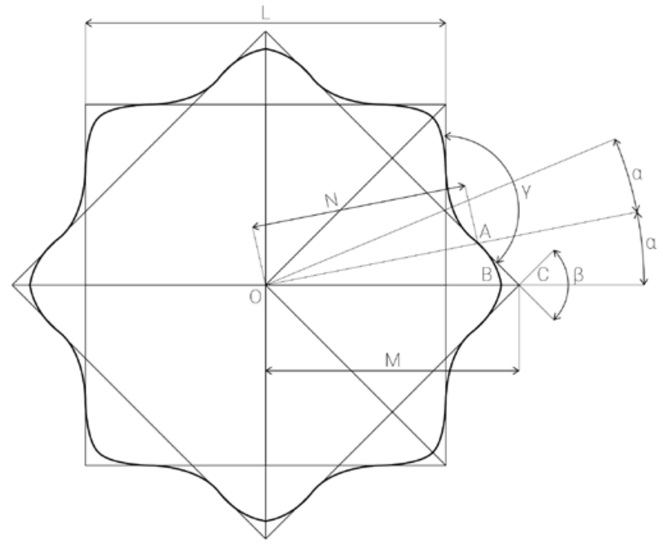
refer to the parametric design methodology (Burry, 1996). Thirty years ago, given the emergence of these three-dimensional modeling systems, the work required the involvement of mathematicians and programmers. Over time, the skills of these different professions have become intertwined and more synthetic - pointing to shifts in professional and educational boundaries.

In the piece "Models, prototypes and archetypes fresh dilemmas emerging from the'file to factory'era", in *Manufacturing the Bespoke* (Sheil, 2012), Burry summarizes the design phases that have been carried out to digitize (Fig. 4.11) the Nave Columns, the Rose Window of the Passion Facade and the Glory Facade. The digital formulation required an interpretative operation for the definition of the underlying geometric and generative principles in Gaudi's work (Fig. 4.12). A theme that the Catalan architect has proposed in a recurring way, for example, is the use of the intersection of polygons "with consequential apex and re-entrant angularity softened by using respectively contangential convex and concave parabolas to form the undulating base profile in all the columns" (Burry, 2016). This is the case of the Nave Columns whose volume, from design indications divided into four hierarchical orders, is generated by the opposite rotation of triangles, squares, pentagons and hexagons, in which one profile rotates clockwise and the other counterclockwise.

Once the generative principle was defined it was necessary to interpret the correct proportions suggested in the study models (Fig. 4.14), to then be transferred through robotic fabrication (Fig. 4.13) to full-scale (Fig. 4.16, Fig. 4.17). The work in the digital environment is thus configured as a critical process of evaluation and tectonic analysis, made systematic by the parametrization of primitives. Architects then turned to descriptive geometry, instead of "attempting to extract data from the surviving model fragments, involving a time-consuming trial and error approach" (Burry, 2004). The digital computation for this project[83] has meant the possibility of investigating formal systems "in ways that Gaudi himself would not have been able to do in his time because of the attendant computational difficulties that contemporary digital design methods can otherwise attempt to resolve with a higher likelihood of success" (Sheil, 2012).

The updating of production methods and the use of increasingly sophisticated tools is a consequence of the customization desired by Gaudi of each architectural unit making up the construction system of the Sagrada Familia, "in an innovative relationship between form and function" (Gramazio et al., 2017). Each column is unique, there are no mirrored volumes and the use of digital fabrication was essential to contain labor costs, whose work carried out using traditional methods (hand carving) would have required an order of magnitude of many hundreds of per cent extra labor. In the proceedings of the biennial conference *Rob | Arch 2016*, Burry defines the three main steps of what has been defined as the digitally assisted stereotomy (Burry, 2016).

83 Mark Burry's lectures at the AA School of Architecture in London. Antoni Gaudi and the Status of his Drawings and Models (2006): https://www.youtube.com/watch?v=DKEhWLr9bsg&t=3901s. Scratching the Surface of Parametric Design Possibility (2014): https://www.youtube.com/watch?v=PnYSFngpT1U.



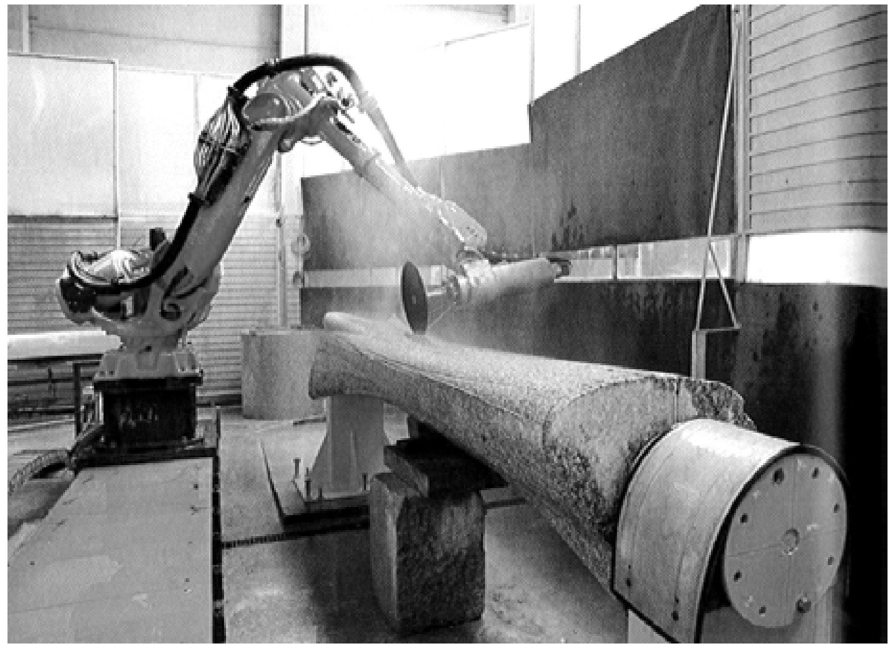


Fig. 4.12 Geometric description of the section profile of a nave column for the Sagrada Familia church, defined by concave and convex parabolas. Source: Burry, M., 2011. *Scripting cultures: Architectural design and programming*. John Wiley & Sons. p.101.
Fig. 4.13 Production of one of the narthex columns of the Sagrada Familia with a 7-axis robot. Source: Burry, M., 2012. Models, prototypes and archetypes fresh dilemmas emerging from the'file to factory'era'. In: *Manufacturing the Bespoke*. AD Reader. p.48.

1989 - onwards: 2 ½ D robots

The use of 2½D robot saws were introduced for the construction of the 14 meter high Ship columns. This technology is vision-based and uses feedback information extracted from a vision sensor (a camera that collects two-dimensional images) to control the motion of a robot. The name 2½D indicates the fact that the real-time feedback system does not need any geometric three-dimensional model of the object. The circular saw is controlled by a numerical control code and the speed depends on the type of stone to be carved: Montjuic sandstone, granite, basalt, and porphyry. Each column was defined in 112 pieces. The articulation of the cutting planes and the time required for the instrument to assume the correct position before touching the stone meant that the production of each piece took 36 hours to cut. To speed up the process, the use of a 2D digitizer was integrated and a drawing board next to the robot saw on-site. The information to guide the saw blade was extracted from a hand drawn profile and the g-code[84] was generated. This mix of analog and digital tooling on-site suggests a softening of the binary persistent intellectual position of hand versus computer, where a mix of the two often results in the best solution.

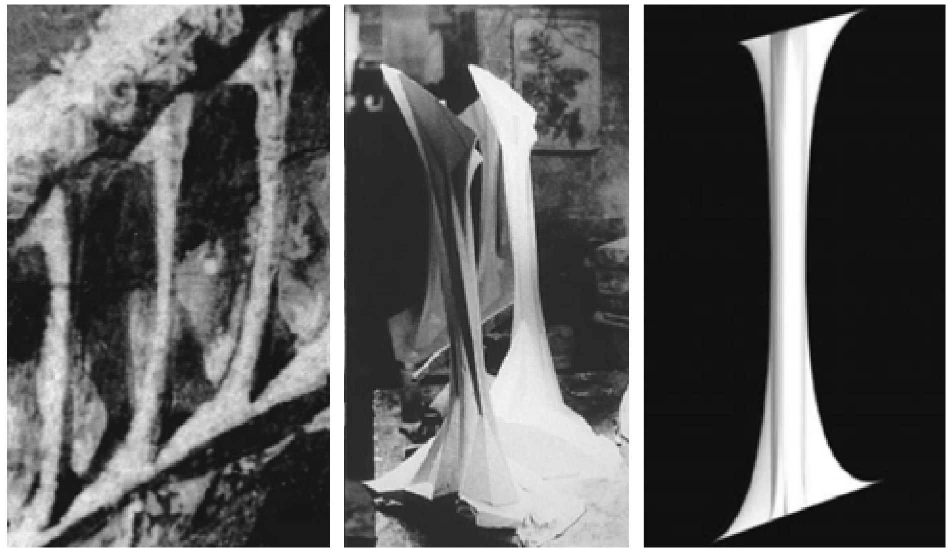
2000-2001: hybrid digital-analogue

The advent of the 2000's coincided with the introduction on a global scale of rapid desktop prototyping technologies. This prototyping innovation coincided with the creation of the Passion Facade Rose Window. To speed up production, the project was based on a "just in time" workflow, so the components of the volume were created, respectively, on-site, in a quarry near Barcelona and in Australia. The procedure was hybridized so that the stonemasons took care of roughing the stone with a first rough cut. This block was then carved following the profiles of the design section using a diamond-encrusted wire saw, a technique that requires the wire to be stretched between two wheels, with the stone block to be placed in between. The last centimeter of the process is left to manual intervention. At the conclusion of this phase of the project, it made clear the potential for a fully integrated digital fabrication process.

2001-2015: use of 7-axis robots

The most recent design-related innovation employed the use of a 7-axis robot for subtractive stone processing (Fig. 4.15). This advancement was possible thanks to a collaboration with stonemasons based in the vicinity of Barcelona that have expanded their technical knowledge from the tradition of stone cutting with the use of advanced automation tools. As Burry explains, the seventh axis made the difference in reducing the number of stone pieces that make up the columns. The possibility of the mechanical arm to slide on a track allows the robot to operate with large material units such as a column 9 meters high is defined only by three parts: base, shaft, and capital. Robotic digital fabrication has meant quality of the result, in fact, "despite the sculptural complexity of the facade, it was constructed with absolute precision to the millimeter" (Burry, 2016).

84 G-code is is the common name for the numerical control (NC) programming language. The G-code provides a machine information about positioning, speed, and path to follow.



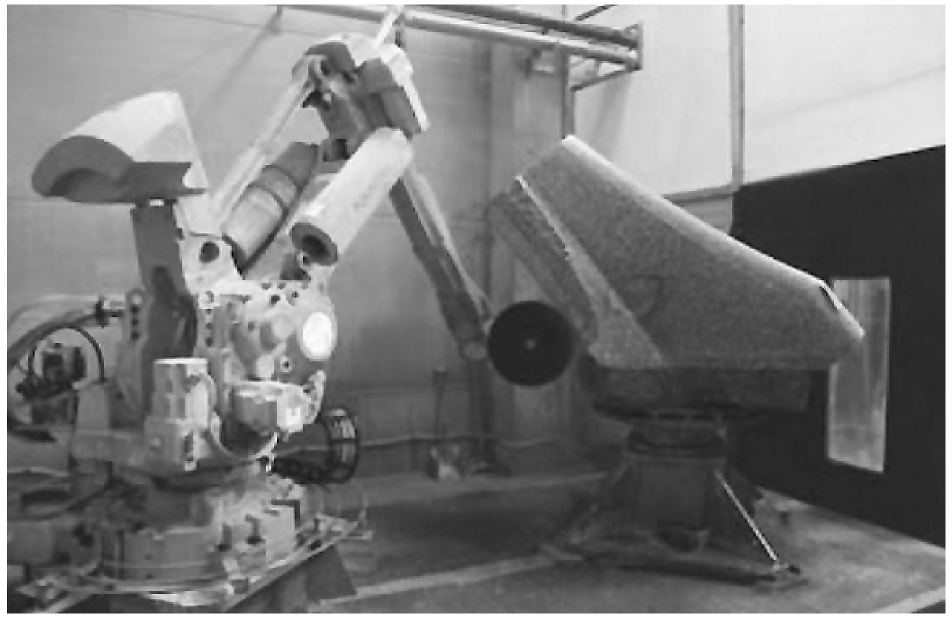


Fig. 4.14 Interpretation of the geometry of the Sagrada Familia's Passion Façade from Gaudi's hand-modeled maquettes. Source: Burry, M., 2016. Robots at the Sagrada Familia Basilica: A Brief History of Robotised Stone-Cutting. In *Robotic Fabrication in Architecture, Art and Design 2016*. Springer, Cham. p.11.
Fig. 4.15 The process of milling stone to make full scale columns following Gaudi's geometries through robotic fabrication. Source: ivi, *Robotic Fabrication in Architecture, Art and Design 2016.* p.12.

How will the construction process evolve in the decade 2020-2030? Today the industrial production technologies are approaching the sectors of architectural and artisan production. In parallel, although not yet systematized on a global level, an update of competences is underway aimed at managing complex projects with decreasing use of economic resources and reducing implementation times. If digital design today is fully part of architectural practice, in the near future "we are moving rapidly from an era of being aspiring expert users to one of being adept digital toolmakers" (Burry, 2011).

The use of robotics has demonstrated the possibilities of accuracy of digital workflows for heritage interventions. It is not excluded that in the next few years industrial machines will be accessible to such an extent that they will be more widely distributed within the Barcelona construction site. Additionally professionals will use AR to simulate virtually the missing geometries before proceeding to manufacture and further minimize potential dimensional deviations.

The interfaces for the coding of the machines will be defined in order to facilitate the dialogue between designers responsible for the geometric resolution of the volumes and the stonemasons that will be able to offer feedback based on the knowledge of the subject on which to carry out the work. As mentioned in Burry's essay "Homo Faber", Gaudi believed that the risk in production should be kept to a minimum.[85] He preferred to use traditional construction methods, leaving the characteristics of innovation to the design phase. However, to be able to complete the work "in his final years he began to realise through experimentation that new materials and methods would need to be introduced to the project" (Burry, 2005).

The Sagrada Familia project defines a milestone in the state of the art of large-scale robotic digital fabrication for several reasons:

- **it is a large-scale application of the most advanced digital tools;**
- **it is a project that required the definition of an iteration of complex workflows, starting from digital computation to CAD-CAM transfer of intersected surfaces such as helicoids, hyperbolic paraboloids, and hyperboloids of revolution;**
- **it employed robotics for large-scale production of customized architectural elements.**

Moreover the Sagrada Familia case study, from the point of view of cultural legitimacy, provides a multi-decade reconstruction as a component of dialogue between digital manufacturing and craftsmanship for a culturally relevant testbed: "it entered a post digital era as a leader, in circumstances where the continued contribution of the craftsperson is judged as a crucial partner to the digital dialogue" (Burry, 2005).

85 Sagrada Familia: pre and postdigital design development, in *Homo Faber*, pag. 36: "Gaudí insisted that innovation must be in the design, not in the making, arguing that traditional methods should be used in order to keep risk to a minimum. In his final years, however, he began to realise through experimentation that new materials and methods would need to be introduced to the project, which can be seen with the construction of the finials on top of the first four towers, with his inevitable uptake of concrete having avoided its use from the first".

Fig. 4.16 Full scale Passion Façade columns, ready to be installed. Source: ivi, *Manufacturing the Bespoke*. p.53.
Fig. 4.17 Passion Façade under construction. Installation of eighteen columns produces by parametric 3D modeling and full scale robotic fabrication. Source: ivi, *Robotic Fabrication in Architecture, Art and Design 2016*. p.13.

4.4.2 Reconstructing memory: digital fabrication of the arch of Palmyra

Numerous conflicts[86] are taking place in some regions of the world[87] and they are the result of multiple causes that lead to the emergence of scenarios of damage, destruction, or loss of the collective cultural-historical heritage (Fig. 4.19). These emerging emergency conditions include but are not limited to environmental discomfort due to natural disasters[88] and single, or multiple vandalism actions. These events can determine, first of all, consequences on the redefinition of the morphological and geological aspects of the territory, compromising the relationship between people and the identity of their geographical areas. In particular, the deterioration of artefacts in sites of historical relevance has an impact on memory and on the collective sense of continuity with the future. These artefacts are invariant elements that international organizations define as a representation of the set of intangible characters[89] of the Cultural Heritage of a population. Armed conflicts often result in the destruction of iconic structures belonging to the past, implemented in an attempt to annihilate the historical identity of the subjects who suffer the aggression. Such socially relevant destructive events, set in a scenario of globalization, can be understood as the process of dissemination of knowledge at an international level due to the systematic refinement of the most current means of communication (Anheier and Isar, 2011). Because of this global communication and dissemination it is possible to create immediate repercussions, at different scales, in the world.

In 2012 the IDA, Institute of Digital Archeology, was founded.[90] It is an organization focused on applied research of digital systems for the preservation of the world historical-artistic heritage. In line with European innovation policies (see Europeana or EU-CHIC), the IDA acknowledges the progressive need to identify repeatable and shared methodologies for the conservation and recovery of heritage that can be applied promptly in different geographical areas.

86 The section "Reconstructing memory: digital fabrication of the arch of Palmyra" was published in the Italian journal *L'Ufficio Tecnico* in issue 7/8 July/August 2016, pp. 12-21, edited by Maggioli. The single-author paper "Processi innovativi di conservazione e recupero del patrimonio culturale (Innovative processes for conservation and restoration of Cultural Heritage)" was reviewed by a member of the scientific committee.

87 Map of the ongoing conflicts around the world: http://www.cfr.org/global/global-conflict-tracker/.

88 There are many case studies concerning the damage to Cultural Heritage due to natural / random events. The earthquake that occurred in 2006 in Iran with its epicenter in the city of Bam (a fortified medieval center representative of the implementation of vernacular techniques applied to the use of raw earth), for example, determined the almost total destruction of the historical plant . See: http://whc.unesco.org/en/list/1208. In 2012 in Emilia-Romagna there was a seismic event that involved the provinces of Modena, Ferrara, Mantua, Reggio Emilia and Bologna, to the detriment of numerous rural and industrial buildings, as well as historical monuments. See: http://whc.unesco.org/en/documents/119948/.

89 The Convention for the Safeguarding of the Intangible Cultural Heritage adopted by UNESCO in 2003 defined as immaterial Cultural Heritage the multiplicity of oral traditions, social practices, expressions of life, knowledge, skills for handicraft production that the communities, groups or sometimes the individuals inherited from their ancestors and are oriented to pass on to descendants. See: http://www.unesco.org/culture/ich/. Tangible Cultural Heritage is defined as the set of physical artifacts that a group or society has inherited from past generations, maintained in the present and conferred for the benefit of future generations. See: http://www.unesco.org/new/en/cairo/culture/tangible-cultural-heritage/.

90 Institute of Digital Archaeology: http://digitalarchaeology.org.uk/our-purpose/.

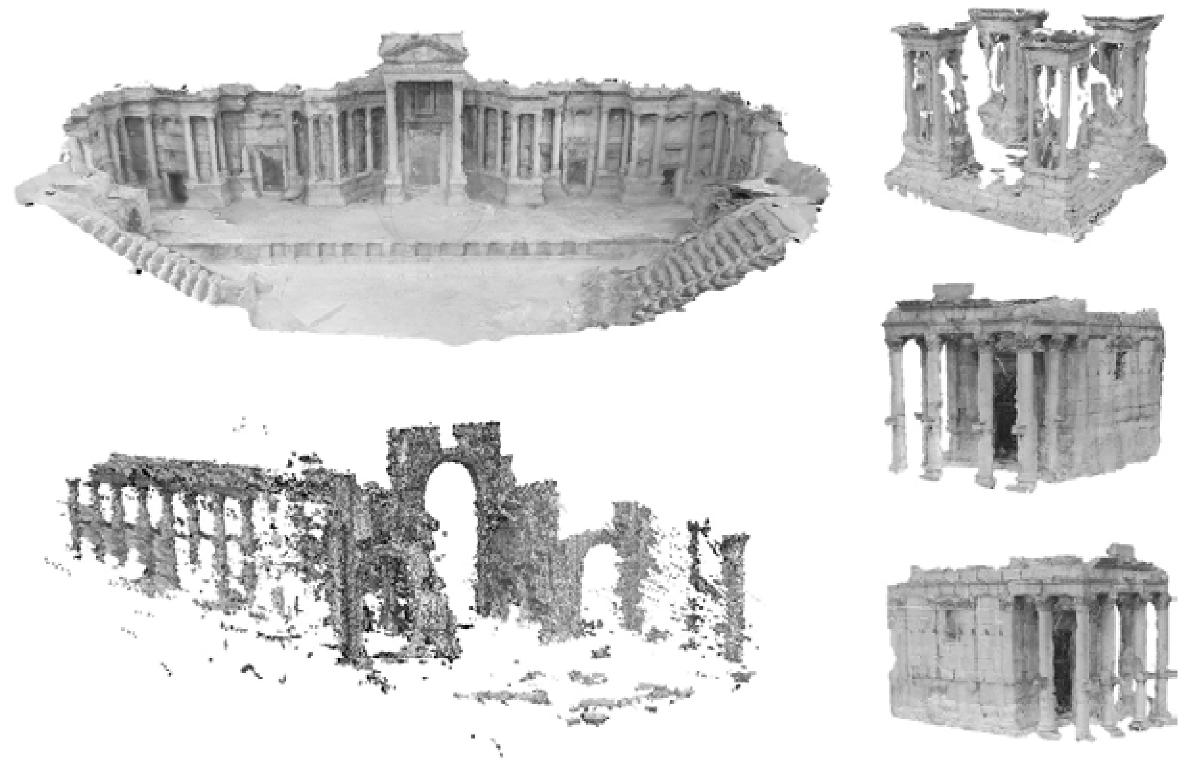


Fig. 4.18 Digital reconstruction of some representative buildings of the archaeological site of Palmyra: the theatre and the monumental arch, the tetrapile and the temple of Bel. The spatial data, defined by a cloud of X,Y,Z coordinate points, have been elaborated with photogrammetric technique, a methodology that allows to estimate dimensional units from photographs taken on-site from different angles. Source: Palmyra 3D Model, https://sketchfab.com/tags/palmyra.

Fig. 4.19 The archaeological site of Palmyra with the remains of the temple of Bel. It was photographed after the episodes of war that led to the damage of multiple finds from the Roman era. Source: courtesy of Directorate - General of Antiquities and Museums in Siria.

In 2015, the IDA sponsored the elaboration of a mapping of archaeological sites and culturally relevant artefacts for the creation of an archive of digital three-dimensional data giving priority to areas subject to political and cultural calamities. The initiative, called The Million Image Database,[91] contributes to the development of an open source platform[92] to trace at any time the geometric and morphological information of the detected assets, even in the event of partial or total loss. Among the works classified as heritage protected by UNESCO, the IDA examined the archaeological site of Palmyra, classified as Heritage in Danger[93] since, when the initiative was launched, the area was inaccessible due to the ongoing civil war on Syrian territory. Through an information campaign, the researchers collected official documentation and photographs taken by tourists and researchers in the years prior to the armed conflict to use the metric dimensional data of the monuments. The images collected were assembled using a photogrammetric technique. It is an indirect measurement procedure for acquiring data relating to the shape and size of an object (Remondino and El-Hakim, 2006) starting from two-dimensional image sequences (Maietti et al., 2016) using software able to process a metric estimation process. This data acquisition logic is frequently put into practice for the 3D reconstruction of component parts (Remondino et al., 2008) and it is also precise for the three-dimensional rendering of objects on the architectural scale (Georgopoulos et al., 2008).

Among the relevant monuments of the site that have suffered repeated damage are the sanctuary of Bel, the temple of Baalshamin, and the monumental arch of Palmyra. The pre-destruction reconstructed 3D models were uploaded to online platforms and available for navigation and download (Fig. 4.18).[94] The arch represented a test-bed for the use of digital fabrication for heritage and for the dissemination of knowledge on global Cultural Heritage. This experimental activity led to the exhibition in London, in the context of the UNESCO World Heritage Week 2016 event, of a scale reproduction of the Palmyra triumphal arch (Fig. 4.22, Fig. 4.23),[95] which construction was coordinated by two Italian companies,[96] supervised by researchers at Magdalen College, Oxford (Kamash, 2017). The prototype was made using the numerically controlled milling technique[97] on the basis of the digital data obtained from the photogrammetric survey. A six-axis robotic arm was programmed to perform subtractive processing (Fig. 4.20, Fig. 4.21) on Egyptian marble blocks, selected for their color characteristics (similar to those of the technological units that make up the monuments of Palmyra)

91 The Million Image Database: http://www.millionimage.org.uk/. To start a shared and participatory campaign that is continuously updated, over 5,000 cameras were distributed with optics mapped between volunteers, academics and researchers. Through photogrammetry, the accuracy of the model results from the number of images acquired, from the environmental lighting conditions and from the possibility of geo-referencing the optics of the cameras, which constitute a fixed control point.

92 Sketchfab is one of the portals that collects data related to the Palmyra site: https://sketchfab.com/tags/palmyra.

93 Heritage in Danger in Syria: https://whc.unesco.org/en/statesparties/sy.

94 Palmyra archaeological site: http://www.britannica.com/place/Palmyra-Syria.

95 Palmyra Arch Replica Is Unveiled in Trafalgar Square in London: https://www.nytimes.com/2016/04/20/arts/international/replica-of-palmyra-arch-is-unveiled-in-trafalgar-square.html.

96 Torart (Carrara), specialized in the field of robotics applied to sculpture and Dshape (Pisa), founded by Enrico Dini, oriented to the design and construction of 3D printers on the architectural scale.

97 Triumphal Arch of Palmyra under construction: https://vimeo.com/161046225.

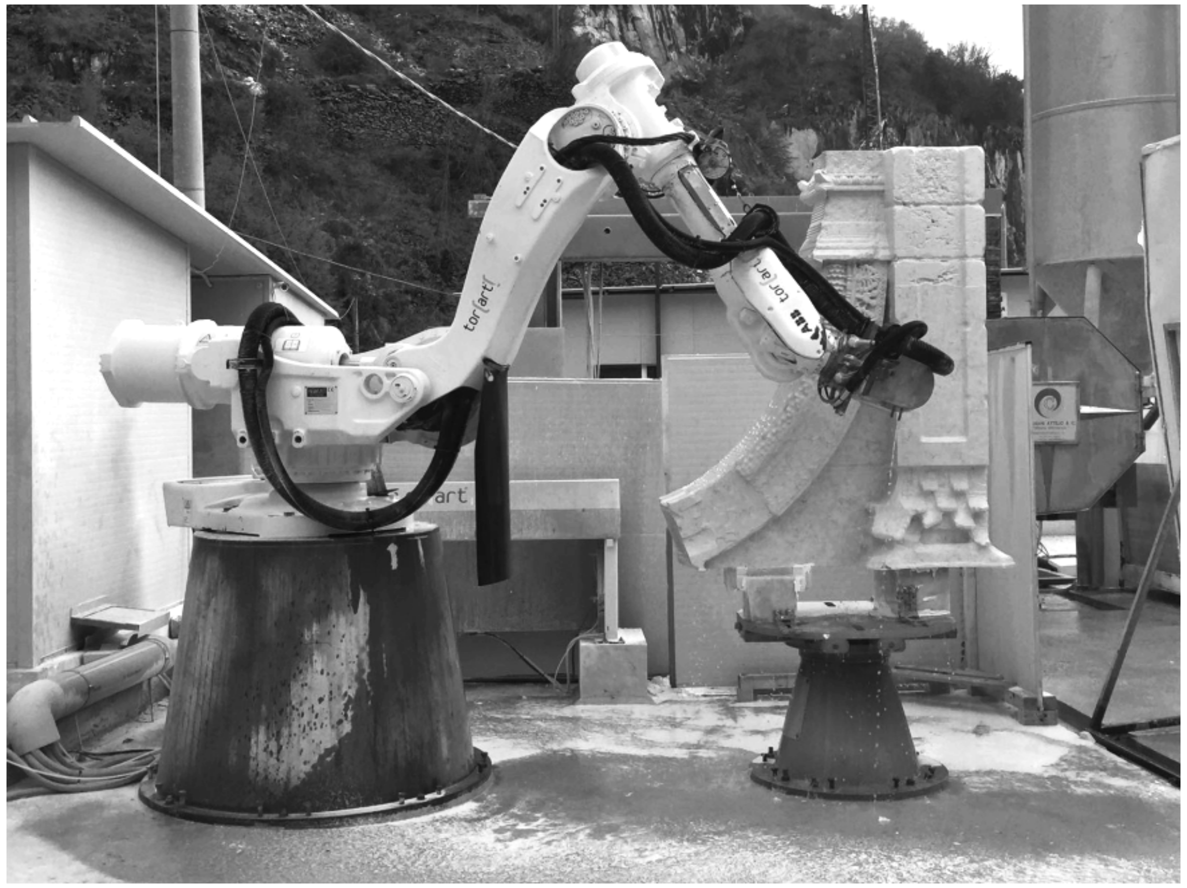


Fig. 4.20 Realization of a block of the monumental arch of Palmyra. The project was carried out by TorArt and Dshape, italian companies specialized in robotics. Source: courtesy of Dshape.
Fig. 4.21 Robotic milling of Palmyra's arch decorative details. Source: courtesy of Dshape.

and for the material processing properties of the stone (Codarin, 2016). Several discrete elements were then assembled to make up the reproduction of the arc. The physical model was created on a 1:3 scale, with the prospect of developing an object of the same size as the original, which is around 15 meters. Furthermore, the availability of adequate machinery and specialized technicians capable of controlling the various and complex procedural phases were located in Carrara which then became the fabrication site. The components were subsequently prepared for shipping to London. The key cost categories for the reconstruction are derived from the use of machinery, from the importation of the raw material to be processed, and from the transport of the finished work to the place envisaged for the temporary or permanent placement. Once this workflow methodology has been validated, the process can be open multiple future instances of improvement.

The 2016 case of the reconstruction of the Palmyra arch represented one of the first examples of dissemination of the technological capabilities acquired by the scientific community in the field of heritage conservation.[98] The experiment[99] can be analyzed according to the following objectives achieved:

- collection of the photographic documentation of the site based on pre-destruction information, due to the lack of a preventive digital survey and the temporary inaccessibility of the area;
- definition of a digital three-dimensional model that can be used to systematize restoration interventions in a post-emergency context;
- tests for the implementation of construction units that can be assembled on the architectural scale using automated tools;
- realization of a scaled-down prototype to verify times, costs, precision, of the robotic instrument in realizing an architectural portion consisting of a decorative apparatus;
- public presentation of the prototype to disseminate the methodology used and promote the preventive processing of digital archives, with priority of the masterpieces and assets at risk through European channels such as Europeana and their respective spin-offs.

A further key point that can be considered as a goal achieved was to encourage, in the following years, the scientific community to open a dialogue between restoration and digital manufacturing (Denker, 2017). Among the hypotheses there is that of evaluating the different robotic manufacturing methods for the implementation phase and the use of robots for numerical control milling or additive manufacturing machines[100] designed to support production on an architectural scale. It is possible to define, by previously testing the feasibility, the on-site prefabrication of discretized units to be assembled on-site, following a standardized workflow that allows the production of customized

98 Digital Tools And How We Use Them: The Destruction And Reconstruction Of Tangible CH In Syria: https://mw18.mwconf.org/paper/digital-tools-and-how-we-use-them-the-destruction-and-reconstruction-of-tangible-cultural-heritage/.

99 The value of recreating the Palmyra arch with digital technology: https://hyperallergic.com/292006/whats-the-value-of-recreating-the-palmyra-arch-with-digital-technology/.

100 The ceiling of the Temple of Bel in Palmyra 3D printed for the exhibition Rising from Destruction in Rome: http://www.tryeco.com/blog/2016/10/04/tryeco-al-colosseo-ricostruzione-del-soffitto-del-tempio-di-bel-di-palmira-per-la-mostra-rinascere-dalle-distruzioni-ebla-nimrud-palmira-dal-7-ottobre/.

Fig. 4.22 Palmyra's arch scaled down replica, displayed in Trafalgar square, London.
Fig. 4.23 Presentation of the replica of the monumental arch of Palmyra on 19 April 2016 in London, for World Heritage Week. The 1:3 scale arch is 5.5 meters high and weighs 11 tons, composed of 70 cubic meters of Egyptian marble and sandstone.

elements. For the additive construction of stone units, the powder-bed deposition technology is adequate, that is to deposit alternating layers of granular and binder material, evaluating to add mixtures with local sands and inert materials. In this way the components of dialogue between new inserts and existing archaeological finds are strengthened. The digital programming of the machines would also allow managing the final architectural image of the reconstructed parts, and defining the formal unit (Brandi, 1963) artifacts without replicating the lost decorative elements but tracing the perimeter or engraving hints at a lower resolution than the original ones.

4.5 The role of the architect: new skills for the digital master-builder

“Handcraft is now an indulgence left over from another century [James Timberlake]

Techno-optimism and techno-pessimism represent a constant pendulum swing resulting from the ubiquity of digital infrastructure that completely covers the technosphere. The most developed areas of the world are in a state of complete dependence on technology. This ubiquity is in stark contrast to the feeling of mistrust provoked by the adoption of the first CAD tools in the 1990's, when the paradigm shift was still attributable to the definition of "digital revolution". Although it did not coincide with a disruptive philosophy of history or ideology of progress (Carpo, 2010). There was a disappearance of the architect in creative processes, “a dissolution of the modern author, whose emergence had once signaled the end of the collaborative practices of medieval lodges” (Carpo, 2010). The current absorption of digital workflows in architecture, with digital transfer from the naval and aeronautic industries, has initiated a process of redefinition of the profession that has its roots in medieval culture. The architectural profession has required construction skills for centuries. In the Middle Ages the designer / craftsperson had the responsibility to manage all the aspects that combine to define a building, from its formal elaboration to the formulation of construction techniques. This proto-professional figure was identified as the master-builder, which is an evolution of the oldest master mason. The master-builder was an architect, builder, engineer, and scientist who used their experience to train successive generations of craftspeople who in turn generated improvements to the tools with new iterations (Fig. 4.24). One of the most important master-builders in history was Filippo Brunelleschi. He oversaw the construction of the dome of Santa Maria del Fiore as well as optimizing the use of traditional materials (King, 2013), herringbone arrangement of the bricks and iron reinforcement of the dome drum, defined the engineering system, and the tools necessary for its construction, such as the technologies for lifting construction materials (Di Pasquale, 2002).

Architectural design and production diverge in the Renaissance, “when designers began to make drawings” (Mitchell and McCullough, 1995). This coincided with the invention of perspective and orthogonal projections as means for the representation of architecture. The redefined conception-production relationship, according to Leon Battista Alberti's conception, is inevitable given the architect's intellectual superiority. The resulting conception of drawings is simultaneously the instruction that the thinker gives to the maker (the building is the identical copy of its representation) and the ideas that have a higher intellectual value than the craft.

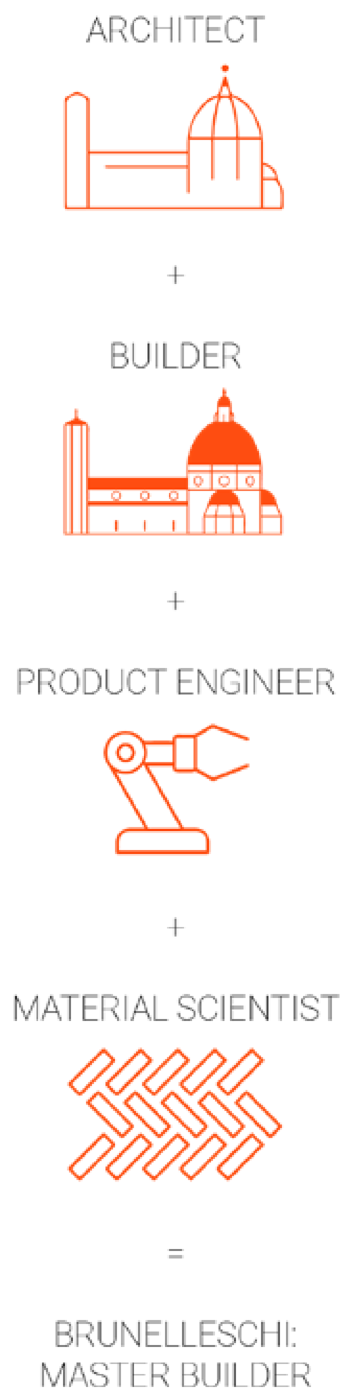


Fig. 4.24 Borrowing Kieran TImberlake's words: "the Renaissance afforded Filippo Brunelleschi the opportunity to be a master-builder due to the relative simplicity of building technology of the time. Source: Kieran, S. and Timberlake, J., 2004. *Refabricating architecture: How manufacturing methodologies are poised to transform building construction.* McGraw Hill Professional. p.26.

The distance between design and built work was further extended in the Industrial Revolution with the introduction of the contractor and the professional engineer. Serial production further marginalized the creative work of the designer as it was no longer necessary to know the materials, their characteristics, and their origins to carry out design work. The marginalization of centralized knowledge occurred in favor of a discretization and automation of production processes. The production of identical standardized copies marks the passage from imitation to the replication of identical copies. The Dymaxion House designed by Buckminister Fuller is a manifestation of this design paradigm of playing out an aerospace manufacturing process for the creation of serial architecture.

The twentieth century has brought a specialization of skills in response to the growing complexity of architectural design and the availability of new materials. This trend toward specialization has transitioned the designer into that of a master-controller, who "coordinates the many diverse consultants who are able to master their own specialities" (Kieran and Timberlake, 2004). The spread of digital workflows in professional practice has meant that architects could use computational data to inform building production. Design time spent previously spent on drawings has been transformed because digital models more closely represent reality, eliminating the necessity of 2D, static drawings. Finally, the Fourth Industrial Revolution (following the phases of hand-making, mechanical-making, and digital-making) and the integration of digital fabrication in the design processes has brought together conception and production again. This reintegration "enabled architects to almost instantaneously produce scale models of their design using processes and techniques identical to those used in the industry" (Kolarevic, 2004). The use of digital technology does not constrain the creative process to the design of standard components, but opens it up to customization. The use of industrial tools (in particular robots) makes it possible to break away from traditional construction methods and to bring design-production even closer together. This alignment brings the master-builder up to date, who "manages to develop a material sensitivity that belongs to the manual skill of the ancient craftsmen through the medium of the machine " (Figliola, 2017). This approach is exemplified in the continuation of the construction of the Sagrada Familia, for which the CAD-CAM (computer-robot) relationship has made historic reinterpretation possible. In this instance the digitisation is done through the use of the same tool, of the medieval way of building.

The separation between designer and maker is compressed by the tool in use. "Computer use is medieval and modern".[101] Branko Kolarevic provides a further specification to the digital artisan-architect, describing them as an information master-builder who "digitally generate construction building information directly from design information" (Kolarevic, 2004). In this sense, the architect can be considered a digital builder, capable of eliminating the unnecessary steps that occur in current design and execution processes.

101 Mario Carpo: "The Second Digital Turn". Talk at Google: https://www.youtube.com/watch?v=UVerq5DSdKU (from min. 51:00).

The close designer-machine relationship allows for the actualization of Louis Kahn's vision of considering cranes as an extension of the designer's arm (Kahn, 1960). Where generic mechanics or "universal machine" (Scheurer, 2012), not specialized in a specific activity, might replace human musculature. However, Professor Antoine Picon[102] in *Made by Robots* formalizes a more complex approach to the question: "the best way to envisage with robots is not necessarily to consider them as an extension of the human mind and body. For they do not exactly replace human arms and hands; they follow principles of their own, often different from the rules that govern human productive gestures". Even more radically: "what remains to be explored is the potential of the machine to emancipate itself from the instructions of the designer, in order to appear as a significant other in the conception of the project" (Picon, 2014). According to Picon, if we do not consider the tools for the digital fabrication of simple project idea performers, it is possible to identify greater learning opportunities and an increase in the skills that the architect will need in the near future:

- **the robots make the designer train to think in three-dimensional space, without privileged directions (although gravity forces the consideration of horizontal from vertical). The use of tools that expand the work area leads to making abstract operations or spatial operations and mechanical motions that derive from the design decisions taken;**
- **the robots encourage the designer to make the lines that distinguish digital-physical, process-result, and sensory-computational ever more subtle. In other words, to get out of the limits of the drawing sheet to start thinking again on a 1:1 scale;**
- **robotic fabrication allows exploration of a new aesthetic of the building, which emerges from the efficiency of the processes and from the possibility of making numerous iterations with increases in complexity and operational solutions for optimization.**

There is a future opportunity for the architect to explore new digital materialities, operating as a digital builder, or even more extreme a "digital tool builder", (Burger, 2012) an algorithm builder, and a cyborg designer "whose intentions are materialized through the action of powerful artificial arms" (Picon, 2014). The construction of experience in practice will make the designer a digital craftsperson (more precisely a post-industrial digital craftsperson). In the definition of Richard Sennett "is not identified by the fact of actually getting one's hands dirty in a workshop, but by intrinsic motivation and the desire to do a job well for its own sake" with a combination of "material consciousness" (Sennett, 2008). The availability of new tools with extreme flexibility still leave room for the individual ability of the architect who will develop the most effective methods of use according to the design circumstances. This new conception allows for an update to the thoughts of David Pye according to which "workmanship using any kind of technique or apparatus, in which the quality of the result is not predetermined, but depends on the judgment, dexterity, and care which the maker exercises as he works" (Pye, 1968). The decision-making phase will increasingly evolve in the direction of fabrication-aware design, encouraging the definition of a cultural paradigm that is grounded in the dialectic between digital and tangible. The skills that derive from the tradition of the profession will not be replaced, but improved and supported by digital tools.

102 Antoine Picon at Harvard GSD: https://www.gsd.harvard.edu/person/antoine-picon/.

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PART III - BRIDGING THE GAP BETWEEN DESIGN AND PRODUCTION

5 Case studies analysis and definition of operative tools

ABSTRACT

The state-of-the-art focused on the digitalization of building processes and the customization of building production for conservation. The case study analysis was used to narrow the research and structure the operative tools to carry out an applied experiment. The experiment explored the technical complexities of using robots that may occur in the restoration building-site.

This chapter is structured in two sections:

1) Case studies on Cultural Heritage

Restoration projects on historic buildings of cultural relevance are described. A taxonomy is used to make the examples comparable. It includes the scale of the intervention, the design approach, the material used, and the technical complexities faced through the realization process. The design approach of the chosen examples is one of autonomy and dissonance with the existing building being restored.

2) Case studies in robotics, divided into the categories (a) disembodied craft and (b) computer vision

Examples of large-scale robotics are presented. The description is structured as a taxonomy that includes the technology readiness level reached with the experiments, the typology of the outcome, the tools used, and the design process adopted. Technical complexities are highlighted, such as the scalability, the level of detail of the outcome, and the lack of predictivity.

An the end, a summary overview is provided to connect the sections. It highlights some relevant issues that should be addressed and solved to open the possibility of using automation on-site. The main challenges concern the interaction of robotics with existing buildings, unpredictable conditions due to degradation, or lack of information about the architectural system. The sorting of the complexities identified, in order of priority, sets the ground for the lab experiment and opens to hypothetical workflows for future applications at the architectural scale.

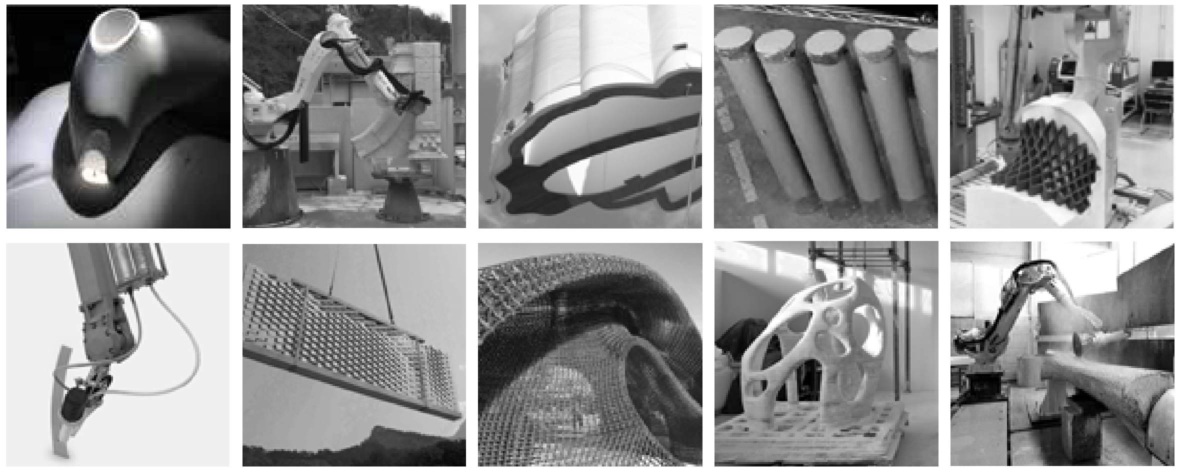
Keywords: A*rchitectural Heritage, Restoration, Robotics, Disembodied Craft, Computer Vision*

CULTURAL HERITAGE

Restoration projects

ROBOTICS

Disembodied Craft



Computer vision

5.1 Architectural Heritage

"Every cultural expression, from the worst to the best, from the most elitist to the most popular, comes together in this digital universe that links up in a giant, non-historical hypertext, past, present, and future manifestations of the communicative mind [Manuel Castells, 2010]

5.1.1 Project selection criteria

This research analyzed different intervention models through which it was possible to deduce unresolved technological aspects, which would benefit from robotic automation of on-site processes. This analytical operation was carried out through the critical study of architectural heritage recovery projects that deploy traditional procedures. To date, there are no similar application cases for which robots are configured as operational tools for execution. Robotic application still remains in the research sector and in the production of off site components.

The selected projects are award winning, published, disseminated, and peer reviewed by international juries. As part of the prestigious awards assigned to these deserving projects, the main reference was to the International Prize Domus Restoration and Conservation Fassa Bortolo (Balzani and Dalla Negra, 2017). The analyzed interventions are aimed at a building heritage to be protected, consisting of those that Cesare Brandi considers in his theoretical essays as "special products", differently from the "industrial products" of the generic building heritage. Attention is paid to those architectural systems that require a value judgment (Dalla Negra, 2016) that directs the designer towards conservative operational choices that are implemented through recovery interventions based on the separation between present and past.

5.1.2 Classification of projects

The analyzed projects fall within the classification that Giovanni Carbonara elaborates in the publication *Architecture of today and restoration* (Carbonara, 2011). The interventions on the heritage are identified according to the different design approaches:

- autonomy / dissonance
- assimilation / consonance
- dialectical relationship / reintegration of the image.

Some representative examples of these categories are summarized below.

Autonomy / Dissonance

Contrast / opposition: deliberate architectural, linguistic and spatial discordance.

Archeological site in Coira, Switwerland[1] (Peter Zumthor, 1986)
Lichtenberg castle in Alsazia, France[2] (Andrea Bruno, 1992)
Sant Augustì library in La Seu d'Urgell, Lleida, Spain (Lluis Maria Vidal i Arderiu, 1994-1995)
Ex-convent Las Capuchinas in Huesca, Spain (Antonio Sanmartin, Miguel Otiz, Leo Rietti, Jose and Maria Valero, 1995-1996)
Hamar cathedral in Norway[3] (Kjell Arve Lund and Nils Slatto, 1998)
Archeological museum in Maa-Paleokastro, Nicosia, Cipro[4] (Andrea Bruno, 1998-99)
Muncheberg cathedral in Germany[5] (Klaus Bock 1998-99)
Furstenberg Castle in Burgusio, Malles, Bolzano, Italy[6] (Werner Tscholl, 1999)
Montemartini Central museum, Rome, Italy[7] (Francesco Stefanori, 1999)
Vigoleno castle, Vernasca, Piacenza, Italy (Marco Dezzi Bardeschi, 1999)
Ex-cemetery in Montesilvano Colle, Pescara, Italy[8] (Marco Volpe, 1997-2000)
Old market, Ortigia, Siracusa, Italy[9] (Emanuele Fidone and Giuseppe Barcio, 1997-2000)
Groenhof castle, Fiandre, Belgium[10] (Samyn and Partners, 1996-2001)
Chiesa di San Pietro della Fortezza di Osoppo, Udine, Italy[11] (Pierluigi Grandinetti, 1998-2001)
Kongresshalle in Nuremberg, Germany[12] (Gunther Domenig, 2001-2002)
Toscano square in Cosenza[13] (Marcello Guido, 2000-2002)
Department of Economy in Battiferri palace, Urbino, Italy[14] (Giancarlo de Carlo, 2002)

1 Archeological site in Coira: http://architettura.it/sopralluoghi/19990901/index.htm.
2 Lichtenberg castle: http://www.diaprem.unife.it/archivio-progetti/progetti-di-comunicazione/focus-r/trento/progettare-il-costruito-perche-e-per-chi-conservare.
3 Hamar cathedral: https://domkirkeodden.no/en/medieval-ruins.
4 Archeological museum in Maa-Paleokastro: https://in-cyprus.com/maa-palaeokastro-archaeological-site-and-museum/.
5 Muncheberg cathedral: http://www.klausblock.de/bauten/sub/muencheberg/muencheberg.html.
6 Furstenberg Castle in Burgusio: https://www.archilovers.com/projects/97290/scuola-agraria-nel-castello-furstenburg.html.
7 Montemartini Central museum: http://www.allestimentimuseali.beniculturali.it/index.php?it/117/allestimenti-elenco-schede/6/roma-museo-della-centrale-montemartini.
8 Ex-cemetery in Montesilvano Colle: http://www.marcovolpearchitetto.it/progetti/edifici-pubblici?AG_MK=0&AG_form_paginInitPages_1=1&AG_form_albumInitFolders_1=progetti/edifici-pubblici/Riuso-ex-Cimitero-Comunale-Montesilvano-Colle.
9 Old market in Ortigia: https://divisare.com/projects/9182-emanuele-fidone-davide-patane-lamberto-rubino-ex-mercato-coperto-di-ortigia.
10 Groenhof castle: https://samynandpartners.com/portfolio/castle-groenhof/.
11 Chiesa di San Pietro della Fortezza di Osoppo: https://casabellaweb.eu/2018/03/14/restauro-e-memoria/.
12 Kongresshalle: https://www.domusweb.it/en/architecture/2002/04/16/confronting-the-architecture-of-evil.html.
13 Toscano square: http://www.marcelloguido.com/projects/piazza-toscano/.
14 Battiferri palace: http://www.archimagazine.com/adecarl.htm.

Gallese tower in Viterbo, Italy[15] (Riccardo d'Aquino and Luigi Franciosini, 2003-2004)
Extension of the Royal Ontario Museum in Toronto[16] (Daniel Libeskind and B+H architects, 2007)

Separation/indifference: overlap of two architectural sub-systems.
Palavela, Turin, Italy[17] (Gae Aulenti, 1961)
Scuderie Quirinale in Rome, Italy[18] (Gae Aulenti, 1999)
Alcalà La Real palace in Spain (Santiago Quesada Garcia, 1999)
Museum of wine in Penafiel, Valladolid (Roberto Valle Gonzales, 2000-2001)
Extension of Moritzburg museum, Halle, Germany[19] (Nieto Sobejano Arquitectos 2005-2008)

Assimilation/consonance

Mimesis/recovery: linguistic continuation and imitation.
Duomo, Noto, Siracusa, Italy[20] (Salvatore Tringali, 2008)
Old Bridge Area of the Old City of Mostar, Bosnia[21] (UNESCO, 2004)
Cathedral of Ferrara (municipality of Ferrara, ongoing)

Analogy/tradition: recovery of compositional principles and techniques.
Echternach in Luxembourg (Leon Krier and Robert Krier, 1938)
Extension of the British School in Rome, Italy[22] (Francesco Garofano and Sharon Miura, 2003)
Extension of the Bank of Spain in Madrid[23] (Rafael Moneo, 1978-79, 2006)

Typological restitution: recovery of the archetype.
Roman theatre in Sagunto, Valencia, Spain[24] (Giorgio Grassi, Manuel Portaceli, 1983-1993)
Reconstruction of the urban fabric of San Michele in Borgo, Pisa, Italy[25] (Massimo Carmassi 1985-2002)

15 Gallese tower in Viterbo: https://divisare.herokuapp.com/projects/326077-luigi-franciosini-porta-di-mezzo-e-torrione-cinquecentesco-nel-centro-storico-di-gallese.
16 Extension of the Royal Ontario Museum : https://libeskind.com/work/royal-ontario-museum/.
17 Palavela: http://www.palavelatorino.it/la-storia-del-palavela/.
18 Scuderie Quirinale: http://www.archidiap.com/opera/recupero-delle-scuderie-del-quirinale/.
19 Extension of Moritzburg museum: https://www.archdaily.com/132838/moritzburg-museum-extension-nieto-sobejano-arquitectos.
20 Duomo in Noto: http://www.lct-architettura.it/public_news/news_Articolo%20Tetto%20&%20Pareti.pdf.
21 Mostar Bridge: https://whc.unesco.org/en/list/946/.
22 Extension of the British School in Rome: https://www.teknoring.com/news/restauro/riqualificare-un-edificio-vincolato-del-1911-studio-amati-architetti-per-la-bsr/.
23 Extension of the Bank of Spain: http://rafaelmoneo.com/en/projects/extension-of-the-bank-of-spain-headquarters-in-madrid/.
24 Roman theatre in Sagunto: https://divisare.com/projects/317637-giorgio-grassi-chen-hao-sagunto-roman-theatre-1985-86-1990-93.
25 San Michele in Borgo: http://www.archcalc.cnr.it/indice/PDF28.2/23_Boschi_et_al.pdf.

Dialectical relationship/image reintegration

Critical reinterpretation: new insertions are at the service of the old enhancing the pre-existing building. It encourages a dialogue between historical and aesthetic instance.

Pietrarubbia village, Pesaro-Urbino, Italy (Arnoldo Pomodoro, 1980's)
Rivoli Castle, Turin, Italy[26] (Andrea Bruno, 1978-86)
Diocleziano baths[27] (Giovanni Bulian, 1980-1990's)
Santa Maria di Lillet a La Pobla de Lillet monastery, Lerida (Lluis Maria Vidal i Arderiu 1992-1993)
Tarragona walls in Spain[28] (Andrea Bruno, 1994-97)
New entrances of Vatican Museums (Lucio Passarelli, Sandro Benedetti, and Angelo Molfetta, 2000)
Oil Museum in Castelnuovo di Farfa,[29] Rieti, Italy (Giuseppe Benedetti, Sveva di Martino, 1990's)
Torre della chiusa di Rio Pusteria in Muhlbach,Val Pusteria, Bolzano, Italy (Josef Rieder 1998-99)
Scuderie Aldobrandini in Frascati, Rome[30] (Massimiliano Fuksas, 1998-2000)
Reichenberg tower in Tubre, Bolzano, Italy[31] (Werner Tscholl, 2000)
Mercati di Traiano in Rome, Italy[32] (Luigi Franciosini, Riccardo d'aquino, 2000-1)

Philology/extension: history is the guide for the modern project. It co-extends the ancient text.
Villa Romana, Piazza Armerina, Enna, Italy[33] (Franco Minissi, 1958)
Apollo temple in Veio, Rome, Italy (Francesco Ceschi, 1992)
Glass paths in Aquileia, Udine (Ottavio Di Blasi Associati, 1997)
Archeological site of Fregellae, Frosinone, Italy[34] (Laura Romagnoli, Guido Batocchioni, Tommaso Gemma, 1991-2001)
Botteghe della via Biberatica, Mercati di Traiano in Rome, Italy[35] (Studio Nemesi 2000-2001)

26 Rivoli Castle: https://www.archdaily.com/910070/turins-castello-di-rivoli-tells-a-story-of-the-regions-history-through-architecture-itself.
27 Diocleziano baths: http://www.archidiap.com/beta/assets/uploads/2015/03/Fantone-Costruire-in-laterizio-78-Bulian.pdf.
28 Tarragona walls: https://constructii.utcluj.ro/ActaCivilEng/download/special/questions_2016/03_Building/03%20B%20QUESTIONS%2017.11.2016-A.Bruno_EN_TR.pdf.
29 Oil Museum in Castelnuovo di Farfa: http://www.beniculturali.it/mibac/opencms/MiBAC/sito-MiBAC/Luogo/MibacUnif/Luoghi-della-Cultura/visualizza_asset.html?id=151814&pagename=57.
30 Scuderie Aldobrandini: https://www.scuderiealdobrandini.com/.
31 Reichenberg tower: https://www.researchgate.net/publication/311068432_A_Virtuous_combat_Werner_Tscholl_Markus_Scherer_Federico_Bucci_Gennaro_Postiglione_A_dialogue_on_castles_and_modern_architecture.
32 Mercati di Traiano: https://divisare.com/projects/326090-luigi-franciosini-mercati-di-traiano.
33 Piazza Armerina: http://www.architetti.san.beniculturali.it/web/architetti/progetti/scheda-progetti?p_p_id=56_INSTANCE_hIz4&articleId=16596&p_p_lifecycle=1&p_p_state=normal&groupId=10304&viewMode=normal.
34 Archeological site in Flagellae: http://www.studiostrati.it/index.php/aree-archeologiche/19-parco-archeologico-di-fregellae-arce-fr.
35 Pedonal path in Mercati Traianei: https://divisare.com/projects/16108-nemesi-studio-luigi-fileticci-passerella-pedonale-ai-mercati-traianei.

Reintegration of the image for conservation: fusion between new and old. It is the expression of a critical-conservative approach.
Alte Pinakotek in Monaco, Germany (Hans Dollgast, 1948-1957)
San Salvatore church in Palermo[36] (Franco Minissi, 1964)
Salomon tower in Visegrad, Hungary (Janos Sedlmayr, 1963-1966)
Reintegrazione of Santa Croce Church in Medina de Rioseco (Jose Ignacio Linazasoro, 1984)
Palazzo De Lorenzo in Gibellina, Italy (Francesco Venezia, 1984)
San Magno ad Anagni crypt, Frosinone, (Bruno Mazzone, 1990's)
Reconstruction of Koldinghus castle in Denmark[37] (Inga e johannes Exner, 1972-92)
Oratorio San Filippo Neri in Bologna, Italy[38] (Pierluigi Cervellati 1997-1999)
Cassero in Prato, Italy[39] (Riccardo Dalla Negra and Pietro Ruschi, 2000)
Bastione delle Forche, Prato, Italy (Giuseppe Cruciani Fabozzi and Carlo Blasi, 1995-2001)
Pie schools church in Madrid, Spain[40] (Jose Ignacio Linazasoro, 1996-2004)
Neues museum, Museums Island, Berlin, Germany[41] (David Chipperfield 1997-2009)

Returning to the macro-groups autonomy / dissonance, assimilation / consonance, dialectical relationship / image reintegration. The selected case studies are evidence of the use of contemporary language for the integration of technological units through "material-figurative transformations for conservative purposes" (Dalla Negra, 2017). This analysis represents an intellectual position regarding the architectural language that it is desirable to suggest an intended use of innovative means of production. The contemporary language can be connected to the other elements of the building (without resorting to neutral solutions) through a non-citationist language that knows how to actualize the "manufacturing masses" (De Angelis, 1995) by inserting them in the contemporary world. The contemporary project for the resolution of the theme of the gaps highlights the dialogue between ancient and technology of our time. These are the types of projects that are believed to be more consistent with the use of digital fabrication. The critical approach that emerged was aimed at considering the CAM tools to expand creativity and design possibilities of the architectural composition to facilitate the implementation of non-standard components to re-function the spaces of historical architecture. This approach can represent a new design paradigm that is an expression of the use of robotics on architectural pre-existing structures.

36 San Salvatore Church: http://www.sansalvatorebeb.it/en/itesoridipalermo.php.
37 Koldinghus castle in Denmark: http://www.kulturarv.dk/1001fortaellinger/en_GB/koldinghus/stories/burned- down-castle-resurrected-as-master piece.
38 Oratorio San Filippo Neri: https://www.architetturaecosostenibile.it/architettura/progetti/restauri-sostenibili-auditorium-ex-oratorio-san-filippo-neri-bologna-232.
39 Cassero in Prato: https://www.instaura.it/restaura-km0/articles/444/il-cassero-di-prato-da-antico-collegamento- difensivo-a-polo-espositivo/.
40 Pie schools church in Madrid: https://www.teknoring.com/news/restauro/jose-ignacio-linazasoro-quando-il-rudere-di-una-chiesa-diventa-un-centro-culturale/.
41 Neues Museum: https://davidchipperfield.com/project/neues_museum.

5.1.3 Criteria of analysis

From the point of view of the cultural approach, the recovery projects that follow were analyzed on the basis of the dialectic between ancient and contemporary language in response to cases of damage such as volumetric losses, wall gaps, damaged fragments, and disassembling. The design aspects of the analyzed projects were supported by the technical aspect, classified according to the scale of the intervention (technological unit, technological subsystem, architectural system) and the contextualization of the new insertions within the architectural system (exterior walls, roof, interior wall, interior floors).

Through the analysis of the project literature, it was possible to analyze a series of technical complexities that concern:

- geometric constraints
- on-site or off-site production of custom units
- structural enhancement
- bandages with carbon fibers, injections of binders, insertion of steel bars in the architectural system, doubling of floor thickness, doubling of wall thickness, "stitch Undoing" interventions
- compatibility of new materials with the existing building
- analysis of the performance, compliance with national / international rules and certifications
- level of detail of the new insertion
- color of the new insertion
- transportation costs
- long production chain of building elements
- chipping, sandblasting, hammering, emery sanding, bush-hammering

It was not the intention to discuss how robots could be used in these projects as an alternative to traditional methods. Instead the objective of the case study analysis was to associate these complexities with the operations of a possible robotic site. Identifying these key points allowed definition of an order of priorities according to which these complexities can be resolved through future experiments in the research sector. Once the issues relating to the robot - surface (or robot - preexisting interface) have been clearly defined, it is intended to structure a laboratory experimentation aimed at solving one of these points and contributing to the advancement of the technology readiness level in this sector.

Design methodologies based on assimilation / consonance through the use of historical materials to repair the buildings were not ignored. However, the rapid developments of the Fourth Industrial Revolution indicate that in the near future the spread of robots on-site will be consolidated and regulated.[42] This determines that the design carried out for complete assonance with the antique obtains a benefit from the automation, which is solely economic. The complete automation of the site limiting as much as possible the use of labor will define an evident efficiency in terms of labor costs and production times.[43] Within the multiple purposes of using automation and robotic systems additional attention should be paid to the creative process as a direct connection between the digital model and physical reality to expand the space of design possibilities. Operating tools deriving from the analysis of case studies.

42 "5 Ways Robotics Will Disrupt the COnstruction Industry in 2019", in *Robotic Business Review*. Available at: https://www.roboticsbusinessreview.com/news/5-ways-robotics-will-disrupt-construction-industry-in-2019/.

43 "Construction Robots Will Change the Industry Forever", in *Robotic Industries Association*. Available at: https://www.robotics.org/blog-article.cfm/Construction-Robots-Will-Change-the-Industry-Forever/93.

Visegrad Tower

Project data

Designer: János Sedlmayr
Location: Visegrad, Hungary
Year of the intervention: 1964

Description

The Solomon's Tower is the traditional name for a 13th-century residential tower in Visegrád, a Hungarian fortified city. In the nineteenth century, the tower was converted into a museum through the restoration project of János Sedlmayr. The architectural language establishes a dialectical relationship with the pre-existent building.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- disassembling

Scale of the intervention:

- **technological unit**
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- interior floors

Materials:

- **dry**
  - stone
  - bricks
  - wood
  - glass
  - metal
- **wet**
  - concrete
  - mortar
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- **production of customized units**
- structural enhancement
- compatibility of new materials with the existing building
- **level of detail of the new insertion**
- **color of the new insertion**
- transportation costs
- **long production chain of building elements**
- **on-site assembly**

Typology of intervention:

- monolithic
- **discretized**

- structural
- non-structural
- **mixed**

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The castle, where the tower is located, was abandoned after the Ottoman-Hungarian wars of the fifteenth century. In the 19th century, the top of the tower was completely missing. In the 1920's, the Hungarian architect Frigyes Schulek designed the restoration project, but it was never completed. The tower, as it appears today ,is the result of the work of János Sedlmayr, realized between 1959 and 1964. Over the centuries, the tower underwent many modifications, as a private residence. The administration rejected Sedlmayr's first project of 1962. According with that plan, the tower would have been rebuilt with iron and glass. The architect's objective was to underline the distance between the contemporary language and the past explicitly, working in dissonance - contrast. Differently from the initial idea, the realized project has a more contained language and creates an elegant relationship between the pre-existence and the new construction. The project also includes the construction of vertical connections. The issue of the wall gap is of particular interest in the development of this dissertation.

Characteristics of the technological system used

The volume of the tower was closed using horizontal wooden strips. They are shaped following the parts of the perimeter wall that remained intact. In this way, the architect restored the building's formal unity with its octagonal configuration. At the top of the tower, the designer elaborated a pedestrian walkway with a lightweight structure made of timber and steel. This architectural solution recalls the presence of ancient decorative details. The entirely collapsed interiors were redesigned in memory of the original vaulted ceilings. The architect used a lightweight metal structure to compose the geometry of the space.

Critical feedback

The project contrasts the tradition by using contemporary materials and languages in a historical building. Before the construction of the new intervention, minor gaps in the walls were repaired using rubble. Then the architect proceeded with the additions. In the project, it is possible to appreciate a design approach that is based on both built and void. The techniques used are highly dependent on the ability of craftspeople, who have made custom components for both the wooden structure (building envelope) and the metal structure (vaulted interiors). The texture used on the facade is relevant. The restoration work for the integration of the wall gap is defined by regular linear discretized elements with a predominantly horizontal pattern. The wooden strips do interface with the irregular geometry of the original stones. Besides, the scale of the wooden strips is smaller than the scale of the stone surface. In this way, the contemporary intervention recomposes the pieces of the past. It does this by playing the role of an ordering element of the architecture.

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Museum of Hamar

Project data

Designer: Sverre Fehn
Location: Hamar, Norway
Year of the intervention: 1969-1973

Description

The project is a restoration of a Scandinavian vernacular building, which was converted into a museum. The restoration work involved the reparation of wall gaps and the reparation of damaged volumes. The architectural language connects history with the contemporary era.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- disassembling

Scale of the intervention:

- **technological unit**
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

- **dry**
  - stone
  - bricks
  - wood
  - glass
  - metal
- **wet**
  - concrete
  - mortar
  - clay

Design approach:

- **autonomy/dissonance**
- assimilation/consonance
- dialectical relationship/image reintegration

Technical complexities:

- **geometric constraints**
- **production of customized units**
- structural enhancement
- **compatibility of new materials with the existing building**
- level of detail of the new insertion
- color of the new insertion
- transportation costs
- long production chain of building elements
- **on-site assembly**

Typology of intervention:

- monolithic
- **discretized**

- structural
- non-structural
- **mixed**

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The restoration project focused on the recomposition of the original architectural image of the building that composed the ancient vernacular system. For the purposes of this case studies analysis, it is relevant to focus on the intervention on the envelope walls. The gaps on the masonry, deriving from degradation and poor maintenance, were cleaned and highlighted as a strength of the project. Sverre Fehn consolidated the remaining stone elements and closed the building volume by installing glass sheets on the outer surface. In this way, the figurative unity of the building is restored and the detachment with the past is established.

Characteristics of the technological system used

The marks left by the passage of time on the building have been restored using glass panes to close the wall gaps. The architect emphasized openings and wall gaps in the building envelope by covering them with glass sheets, attached to the envelope wall with metal pins on each corner. This solution provides an ephemeral contrast to the massiveness of the pre-existent structure.

Critical feedback

The envelope gaps are irregular. Their geometry is unique and complex. The architect visually linearized them by superposing on the surface regular glass sheets. Conceptually, the work on the gap is a simplified geometric approximation. This technological choice required the consolidation of the stone composing the envelope and the production of non-standardized glass sheets, which don't have structural strenght. The project approach was to evaluate every single gap and repair them with a unique solution, following the case-by-case restoration method. The glass helps closing the volume but doesn't help with the building energy comfort performance. For this reason, the architect decided to use this solution adjacently to in-between spaces, where the sealing of the envelope is not indispensable. Consequently, no geometric problems had to be faced, in particular to solve undercuts.

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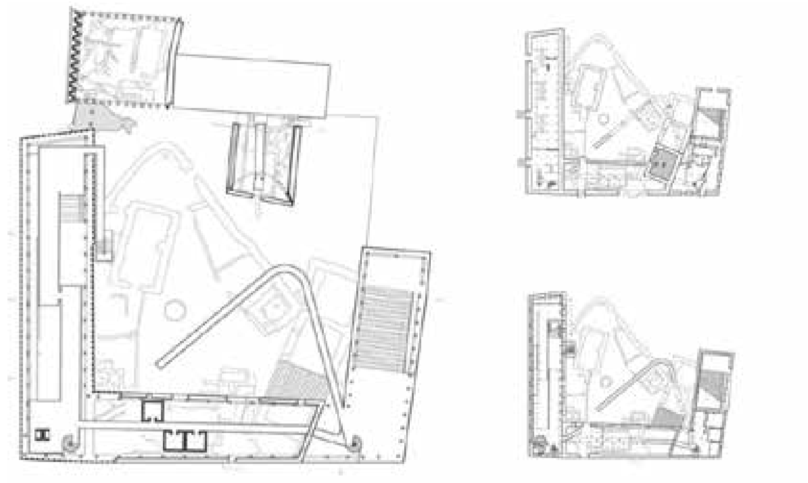
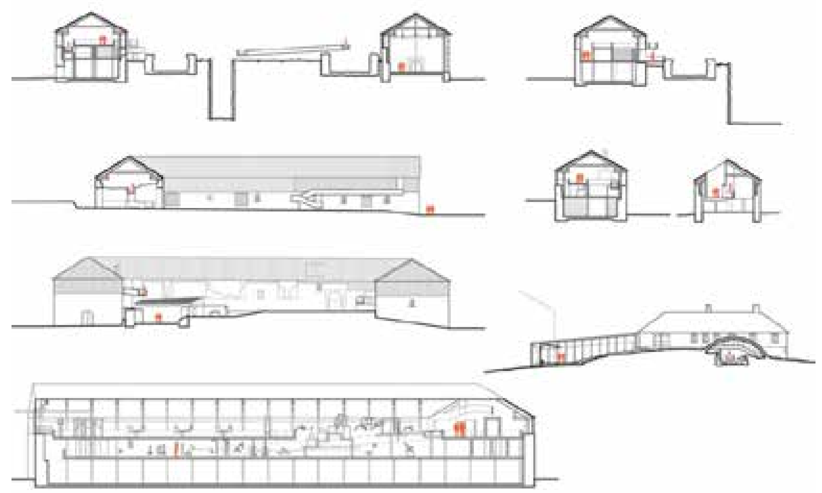




Museo di Castelvecchio

Project data

Designer: Carlo Scarpa
Location: Verona, Italy
Year of the intervention: 1973

Description

The Museum of Castelvecchio is one of the most relevant projects in the field, carried out by Carlo Scarpa. The intervention served to turn the Castle of Castelvecchio into a museum, after it was damaged by the Second Wold War bombing. The project involved reintegrations and volumetric additions. Scarpa also oversaw the museum itinerary and the design of the displays of the works of art preserved in the building.

Case of damage:

- **volumetric losses**
- **wall gaps**
- **damaged fragments**
- disassembling

Scale of the intervention:

- **technological unit**
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

- **dry**
  - **- stone**
  - - bricks
  - **- wood**
  - **- glass**
  - **- metal**
- **wet**
  - **- concrete**
  - - mortar
  - - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- **production of customized units**
- **structural enhancement**
- **compatibility of new materials with the existing building**
- **level of detail of the new insertion**
- **color of the new insertion**
- transportation costs
- long production chain of building elements
- on-site assembly

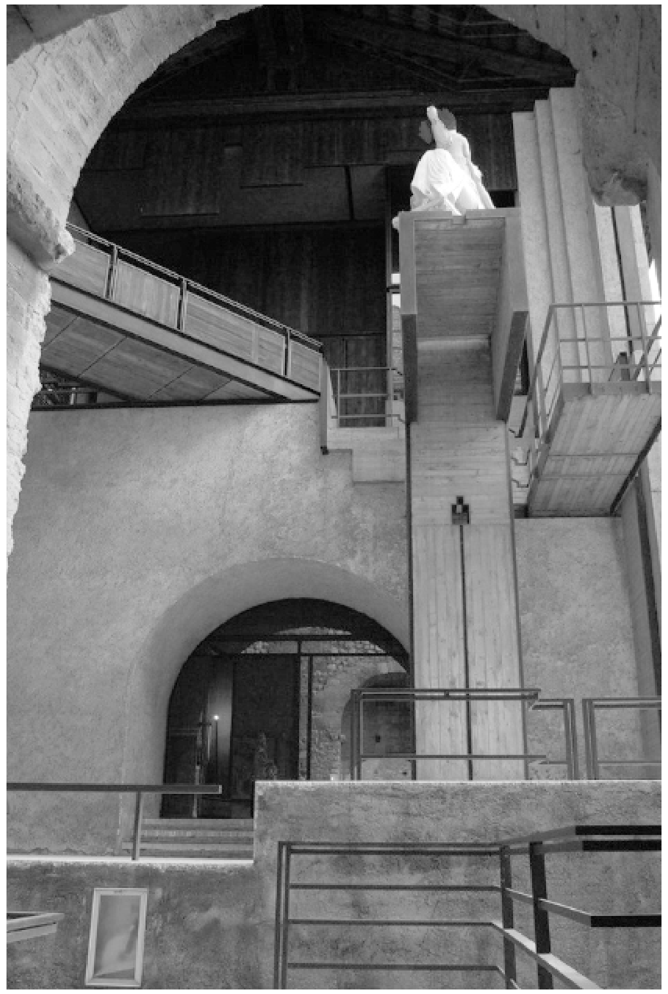
Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The castle was built in the 14th century for defensive purposes. The use changed over the centuries, from a residence to a warehouse, and from a military building to a French academy during the Napoleonic era. In 1924 the castle underwent some repairing works in order to transform it into a museum. In 1956, when Carlo Scarpa took care of the architectural restoration, the medieval castle had already been heavily damaged by the war. Carlo Scarpa considered Castelvecchio a unitary organism on which to intervene, without making distinctions between the restoration of the building and the museographic setting. The intervention proposes enlargements, new distributive solutions and new routes.

Characteristics of the technological system used

Scarpa cuts thorugh the walls to highlight the stratification and articulation of the castle in distinct nuclei, belonging to different periods. This solution helps identifying the medieval Palace and the nineteenth-century gallery of the castle. The façade of the latter, with the central loggia, defines the main internal front of the courtyard, where Scarpa placed the entrance to the museum. The composition by nuclei is also underlined by the placement of paths, stairs and suspended corridors to reconnect structures belonging to different periods. They are made with modern materials and are therefore recognizable as belonging to the layer added by Scarpa. Among these, a system of metal walkways were built. They surround the equestrian statue of Cangrande, which stands on a concrete base.

Critical feedback

The strength of the project is the mediation between the old structure and its renovation. The new museum is modern and designed for a unique and unrepeatable visit experience. Equally unique is the combination of traditional materials typical of medieval architecture, such as pebbles, tuff, and bricks, with contemporary materials, such as the reinforced concrete left exposed. The restoration has an independent language. It is courageous. In this regard, Manfredo Tafuri expressed his opinion on Scarpa's design approach: "what was allowed to Scarpa should not be allowed neither to an imitator nor to a normal professional. [...] Scarpa was able, even by slaughtering a monument, to give us a work of high validity. This happened by the grace of God, and not everyone has the grace".

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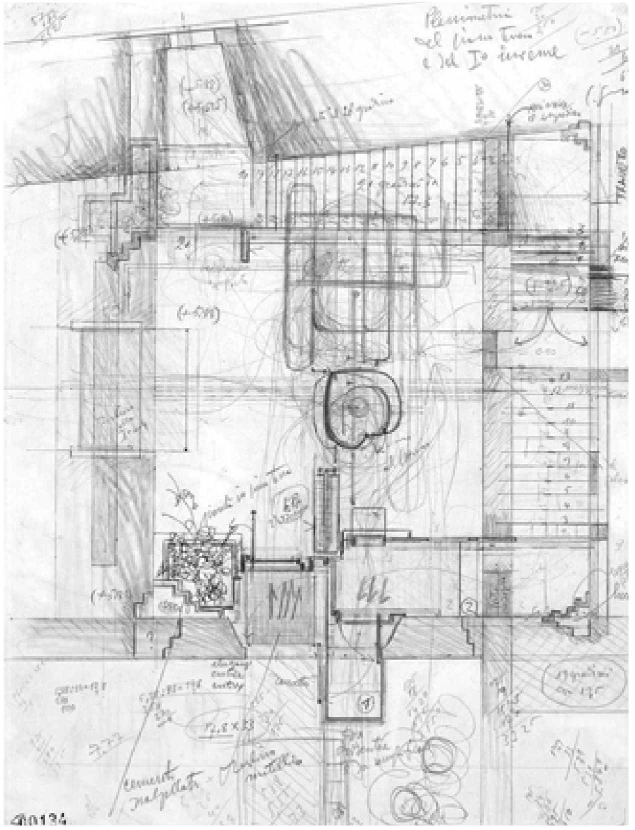
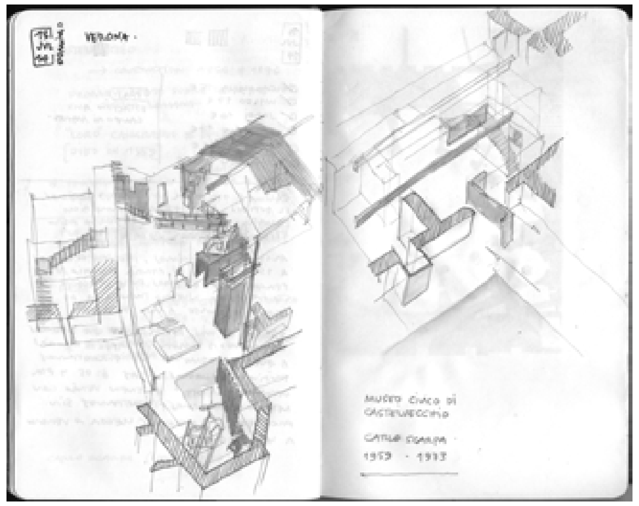




Oratorio di San Filippo Neri

Project data

Designer: Pier Luigi Cervellati and Giorgio Volpe
Location: Bologna, Italy
Year of the intervention: 1999/2000

Description

The project consists in the conversion of the Oratorio dei Filippini in Bologna into a concert hall. The building was designed by Alfredo Torreggiani and damaged by the bombing of World War II. The restoration was carried out by Pier Luigi Cervellati. The intervention looks at the contemporary and at the same time fully respects the traditional construction technologies.

Case of damage:

- **volumetric losses**
- **wall gaps**
- **damaged fragments**
- **disassembling**

Scale of the intervention:

- **technological unit**
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

- **dry**
  - stone
  - bricks
  - **wood**
  - glass
  - metal
- wet
  - concrete
  - mortar
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- **production of customized units**
- **structural enhancement**
- compatibility of new materials with the existing building
- level of detail of the new insertion
- **color of the new insertion**
- transportation costs
- **long production chain of building elements**
- **on-site assembly**

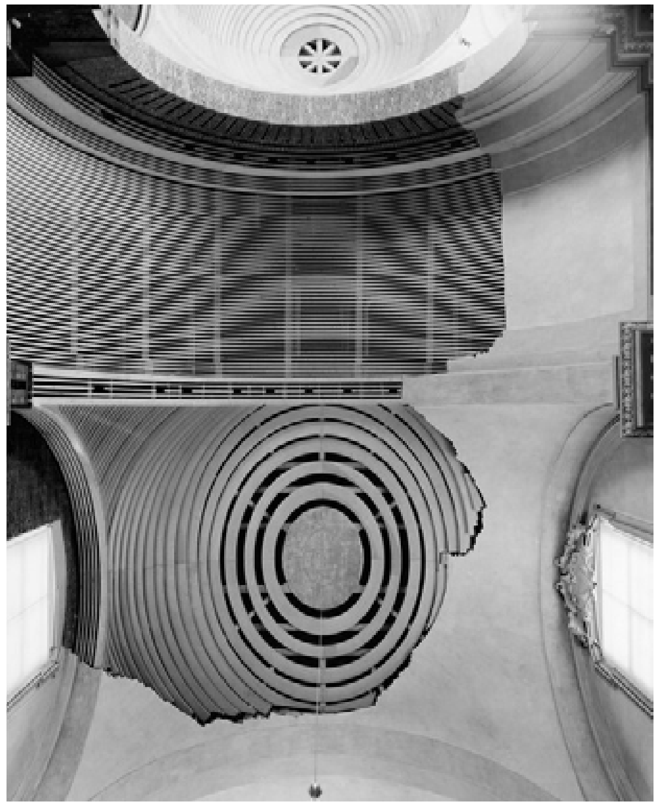
Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The restoration of the Oratory of San Filippo Neri has a long history. In 1944, when the building was bombed, the roof, the vaults, the dome, the right side of the hall, and the apse were destroyed. There was a first attempt to restore it in the late 1940's. The reinforced concrete columns, the brick walls, and the roof with wooden trusses were rebuilt. However, the work was never completed. The building remained unused for the next fifty years. At the end of the nineties, Pier Luigi Cervellati was commissioned to convert the oratory into an auditorium and conference room. The architect worked without cancelling the restoration carried out fifty years earlier and at the same time fixing the persistent structural problems. The overall objective of the project was therefore to repair the damaged volumes and define an internal ceiling system.

Characteristics of the technological system used

The peculiar design element is the reconstruction of the original barrel dome. The project recovers the original shape through a wooden structure made of supporting ribs and battens. The new dome is obtained by spaced contour curves. The wooden structure reflects the structural order of the pre-existing vaults. There are also glulam beams that integrate the load-bearing brick structure, which is consolidated by steel tie-rods and carbon bandages. From a stylistic point of view, the design approach allows for a contemporary reading of pre-existence and contemporary design.

Critical feedback

The first restoration work, carried out immediately after the Second World War, is impactful. It proposed the addition of massiveness in contrast to the fragmentation caused by the bombings. On the contrary, Cervellati's intervention aims at using the lightness of wood as a key material for the execution of the project. Thanks to its intrinsic flexibility, the wooden structure meets the needs of the project, respecting the shape and the thickness of the pre-existing units. The wooden elements continue the structural pattern of the ceiling. This conceptual principle is fundamental for the integration of the intervention in the oroginal architectural complex. The choice to display the structure of the vault is the stylistic trait of this design language, which is a message of memory.

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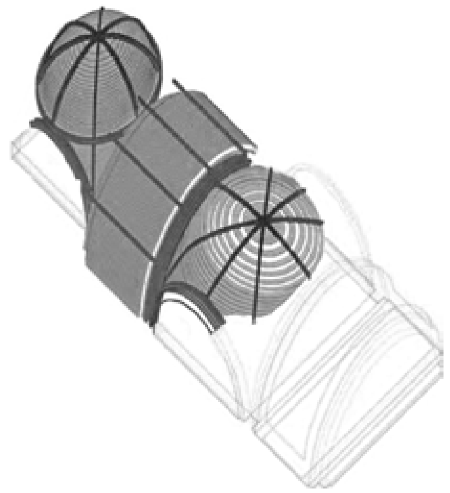

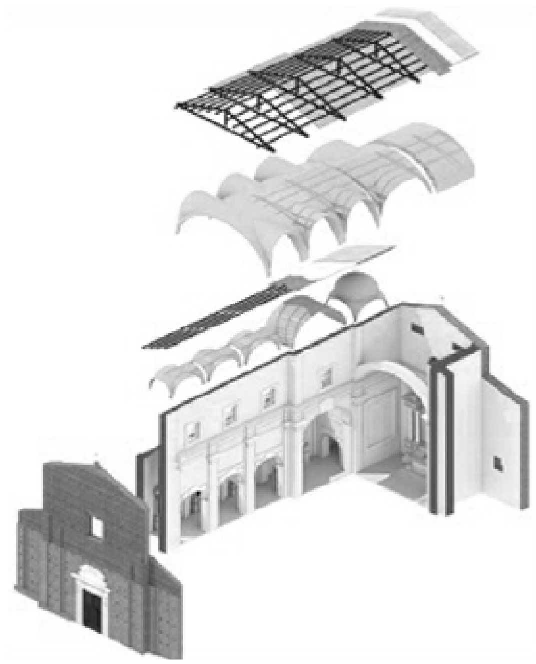

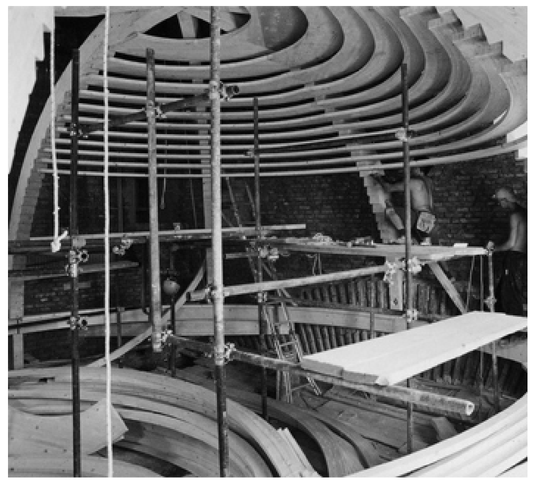

Medieval Cassero in Prato

Project data

Designer: Riccardo Dalla Negra and Pietro Ruschi
Location: Prato, Italy
Year of the intervention: 2000

Description

The Cassero of Prato is a building that was bilt with defensive purposes in the fourteenth century. In 1800 the building was demolished to make space for new roads. A long period of abandonment of the building followed. Between 1980 and 1990 the Superintendence for Environmental and Architectural Heritage authorized its structural consolidation. A new intervention, completed in 2000, gave new life to the building through a conservative restoration, which transformed it into an exhibition centre.

Case of damage:

- **volumetric losses**
- wall gaps
- damaged fragments
- disassembling

Scale of the intervention:

- technological unit
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- roof
- interior wall
- interior floors

Materials:

- **dry**
  - stone
  - bricks
  - **wood**
  - glass
  - **metal**
- wet
  - concrete
  - mortar
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- geometric constraints
- production of customized units
- **structural enhancement**
- **compatibility of new materials with the existing building**
- **level of detail of the new insertion**
- **color of the new insertion**
- transportation costs
- long production chain of building elements
- on-site assembly

Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The Medieval Cassero, originally, connected the small fortress built near Porta Fiorentina with the eastern gate of the Emperor's Castle, where the garrison was based. The connection consists of a corridor of over two hundred meters that allowed the soldiers to reach the castle directly from the city walls without being seen. The internal walkway, 3 meters above the street, is a long connecting volume with a barrel roof and, on the sides, lunette windows alternating with narrow slits that give light to the passage. In the 16th century, the Cassero was progressively abandoned. The restoration, completed in 2000, allowed to recover of the old structure. The project addressed the themes of conservation, structural improvement, and volumetric integration.

Characteristics of the technological system used

The restoration work served to re-establish the connection between the portion of the demolished Cassero and the Castle. This objective was achieved through the delineation of the planimetric outline of the ancient wall, through a cut in the road and the insertion of porphyry cubes to trace lines where the ancient volume was. On the opposite side, closer to the city walls, the pedestrian walkway of the Cassero was rebuilt using wood and steel. The sharp cut that the building had suffered during its partial demolition was used by the architects to graft a new iron and wood frame that eases the access to the inside of the building. Conservation works were carried out also to restore the original surfaces by recovering the old plasters, the masonry joints, and the upper battlements.

Critical feedback

The project faced complexity at all scales, from construction technology, to architectural image, and to urban integration. Interventions on pre-existing buildings require the use of light weight, versatile, and reversible materials. Therefore in this context, as in many other cases, the architects used the combination steel-wood. This solution has structural advantages and eases the assembly of discrete elements. Borrowing the designers' words: 'the creativity inherent in the reintegrative architectural project must not put the addition itself at the centre of attention, assimilating the pre-existence to an evocative and courtly frame, but must draw inspiration from it so that the lack is figuratively reabsorbed by the monument, while using an authentically modern language'.

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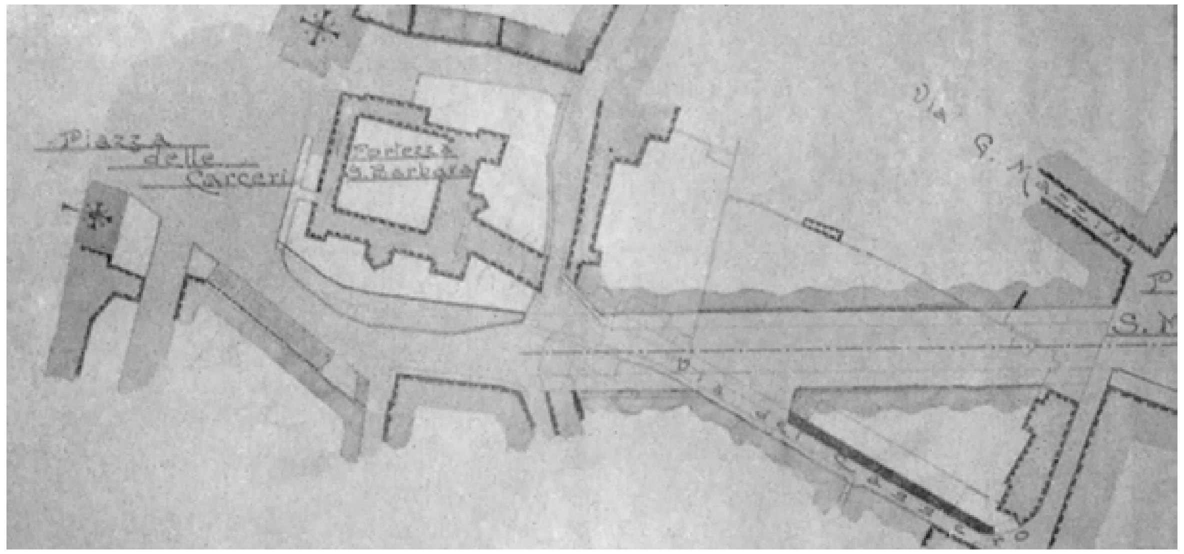

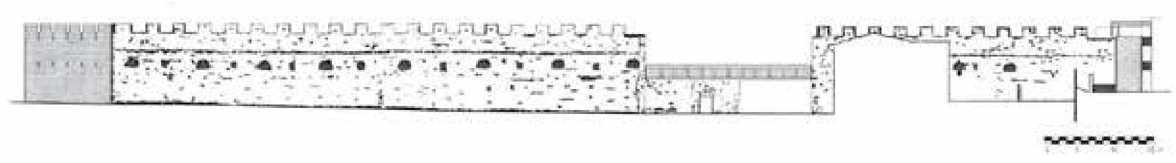

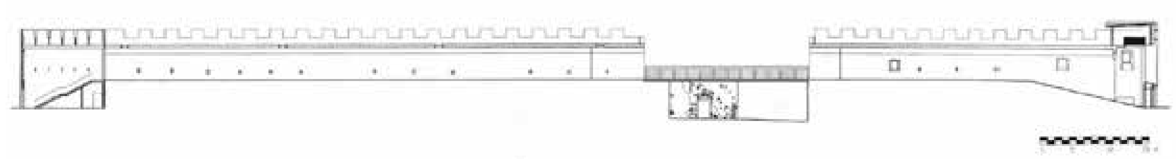

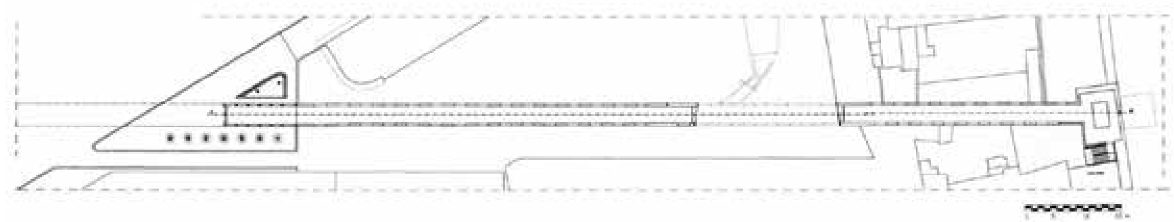

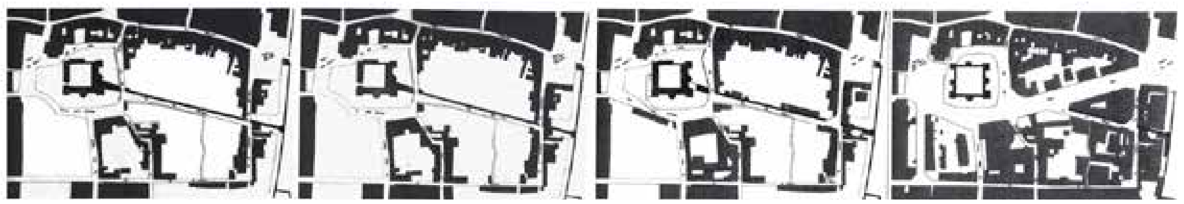

Escuela Pìas de San Fernando in Madrid

Project data

Designer: Linazasoro & Sánchez
Location: Madrid, Spain
Year of the intervention: 2004

Description

The project is an example of reuse and transformation of the ruins of the Escuela Pias de San Fernando in Madrid into a university library. The church was burned down during the Spanish Civil War and remained in a state of decay and neglect ever since. The restoration has recovered its historical narrative and physical memory.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- disassembling

Scale of the intervention:

- technological unit
- **technological subsystem**
- architectural system

Classification of architecture elements:

- exterior walls
- **roof**
- interior wall
- interior floors

Materials:

- **dry**
  - stone
  - bricks
  - **- wood**
  - glass
  - **- metal**
- **wet**
  - **- concrete**
  - mortar
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- production of customized units
- **structural enhancement**
- **compatibility of new materials with the existing building**
- **level of detail of the new insertion**
- color of the new insertion
- transportation costs
- long production chain of building elements
- **on-site assembly**

Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The Escuelas Pías were created in 1734 to offer education to poor and abandoned children. Throughout the 19th century, the school was extended several times. In 1936, during the Spanish Civil War, the church, the school and the convent were raided and demolished shortly afterward. The project is part of a rehabilitation plan for the characteristic neighbourhood of Lavapiés, Madrid. In these ruins, as well as in the lands surrounding them, contemporary functions have been introduced to give new life to the otherwise unusable spaces of the building.

Characteristics of the technological system used

The interior space was adapted to the needs of the library, generating a double-height mezzanine made through the construction of a wooden structure supported by reinforced concrete beams and pillars. In the area of the old presbytery, another triple-height loft space with a similar structure was generated. The bookshelves were placed in the deriving new space. From the presbytery, all other rooms can be accessed. To close the space in the inner part, a false ceiling with wooden slats hanging from curved wooden trusses was built. This solution emulates a vaulted roof, to recall the historical geometry. The trusses transfer the weight on the walls of the building, both on the nave and the circular volume.

Critical feedback

The project works at different scales. It includes urban planning and furniture design. The use of ceramics in the new intervention contextualizes the presence of ruins. In this way, the same material assumes entirely different configurations and expressive significance, both in the restoration project and in the original building. Wood, concrete, and ceramics frame a bare ruin and blend it with new elements to form an original spatiality. This approach emancipates the pre-existence from memory. Thus, the diversity of the building systems used is well-positioned, and clearly integrated. The case study Escuela Pias is a complex project, characterized by the unity provided by the new materiality and the church ruins. The ambiguous character of the covered and uncovered parts underlines the relationship old construction - ruins, supported by the entance of natural light. In the building, different concepts dialogue in a spontaneous way.

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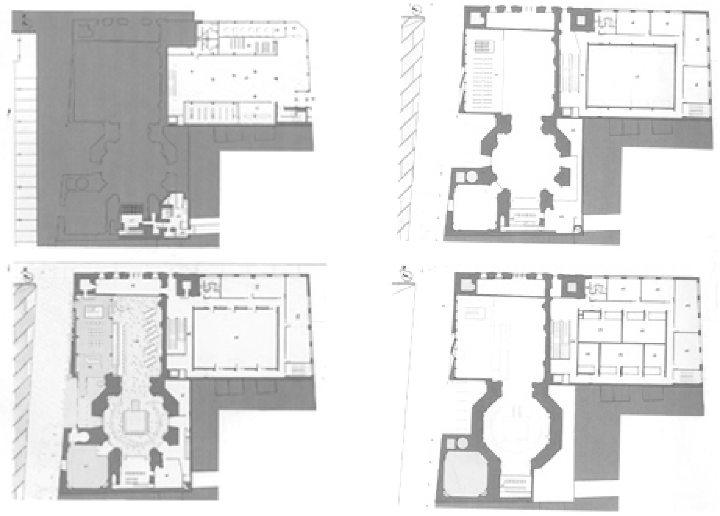
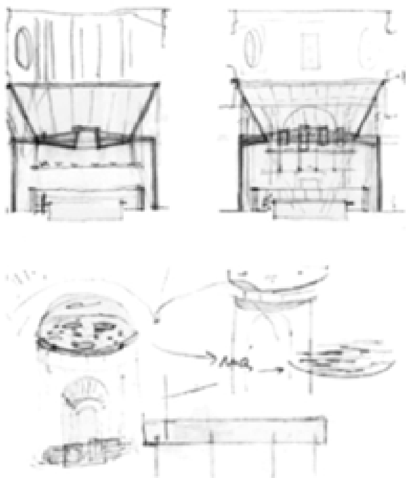
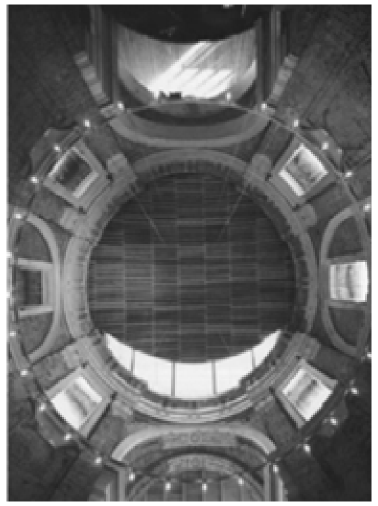
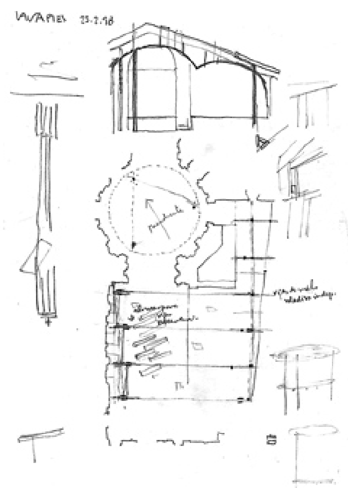
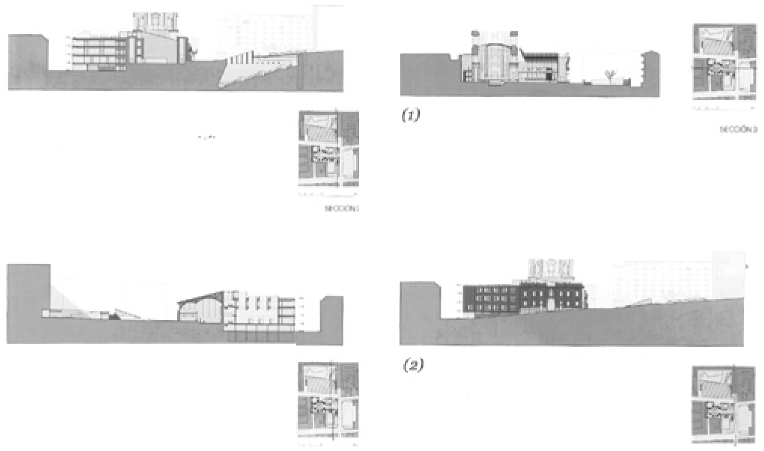










Kolumba Museum

Project data

Designer: Peter Zumthor
Location: Cologne, Germany
Year of the intervention: 2007

Description

The museum is built on the ruins of the Gothic church of St. Columba in the old town of Cologne, which was destroyed during WW2. The project by Peter Zumthor is a testimony of the glorious chapters of the city's past. The site is registered as a landmark with a high historical valu, because of the discovery of Roman, Gothic, and medieval ruins under the old church. Zumthor preserved the ruins and valorized the archaeological site.

Case of damage:

- **volumetric losses**
- wall gaps
- **damaged fragments**
- disassembling

Scale of the intervention:

- technological unit
- technological subsystem
- **architectural system**

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

- dry
  - **- stone**
  - **- bricks**
  - - wood
  - **- glass**
  - **- metal**
- **wet**
  - - concrete
  - **- mortar**
  - - clay

Design approach:

- **autonomy/dissonance**
- assimilation/consonance
- dialectical relationship/image reintegration

Technical complexities:

- **geometric constraints**
- **production of customized units**
- **structural enhancement**
- **compatibility of new materials with the existing building**
- **level of detail of the new insertion**
- **color of the new insertion**
- transportation costs
- **long production chain of building elements**
- **on-site assembly**

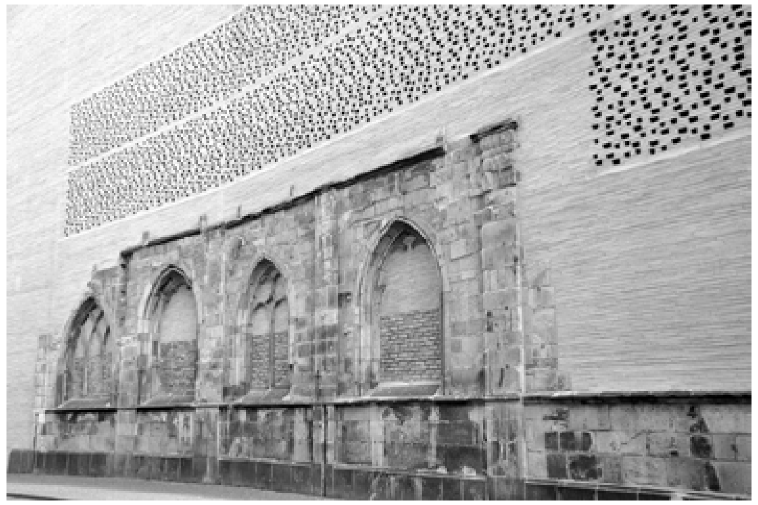
Typology of intervention:

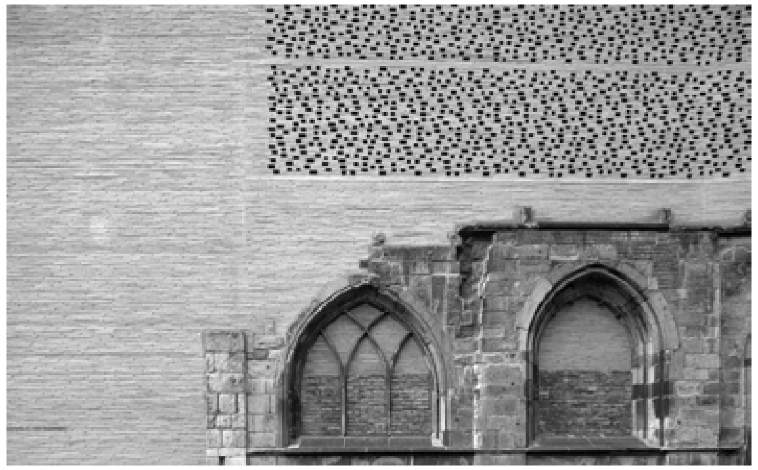
- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**





Performance requirements of the project

Throughout the history of Cologne, several churches were built on the site of the Kolumba Museum since the first Roman settlements. The church in Kolumba was built to demonstrate the power of the parish. It remained standing until 1943, when the site was demolished by the Allied air attack. Since then, the ruins remained largely intact. Through the intervention, Zumthor reconciled the different layers of history, keeping the existing archaeological fragments as identifying signs.

Characteristics of the technological system used

Zumthor used grey bricks over the destroyed fragments of the site. These fragments include the remaining pieces of the Gothic church, the stone ruins from the Roman and medieval period, and the chapel of the German architect Gottfried Böhm, which was built in 1950 in memory of the WW2 bombings. The grey brick façade is the representative architectural element of the museum. Articulated with perforations, the brick work allows diffused light to enter the interior spaces in a textured and changing way through the seasons.

Critical feedback

Among the many valuable aspects of the project, materiality plays a fundamental role in the Kolumba Museum. Zumthor has long sought the perfect material for the context to dialogue with the historical ruins. The mixture of bricks is the result of a process specifically designed for this project. The bricks were individually handmade and fired with charcoal to give a warm tone. The process that led to the production of custom-sized bricks is a representation of the approach of the designer, who works as a master-builder in full awareness of the properties of the materials used for construction. Zumthor customized the project and the discrete technological units that make it up. The bricks are a prototype of a new building product. In parallel, the building is a prototype of a unique and unrepeatable entity that manifested itself through restoration. Moreover, the decision to work adjacently to the existing stone brought to the contemporary world the attitude to restoration that Carlo Scarpa expressed in his work in the 1970's.

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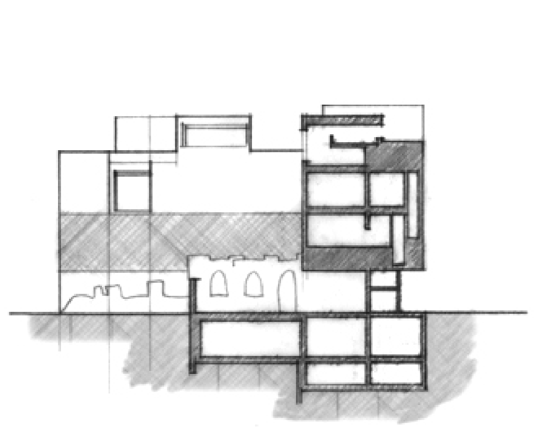

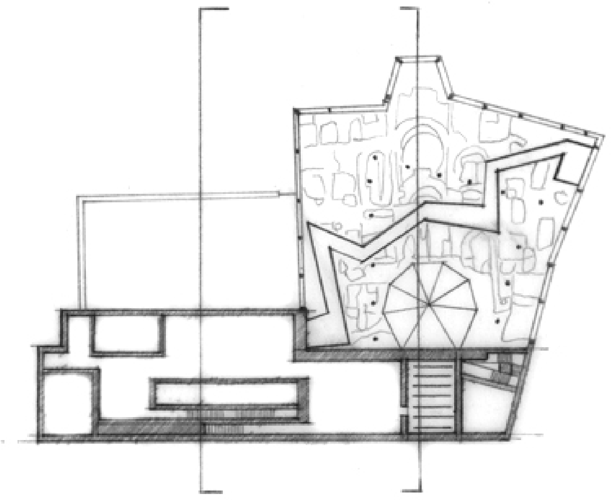

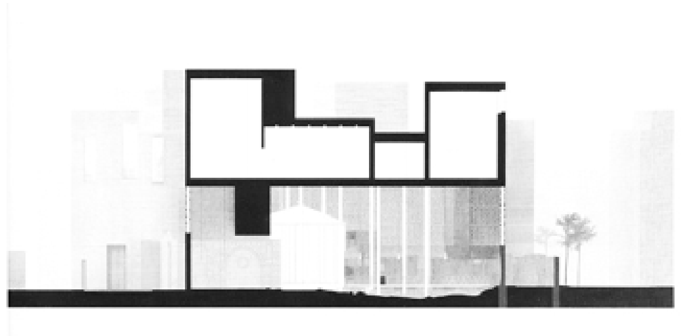

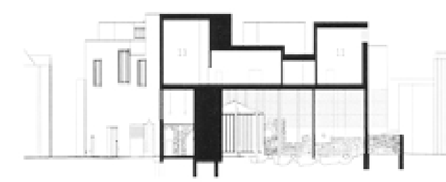

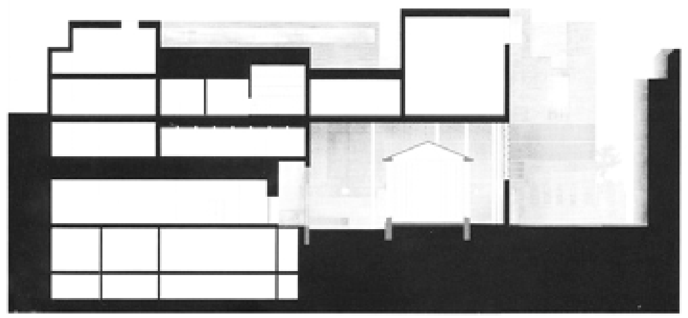

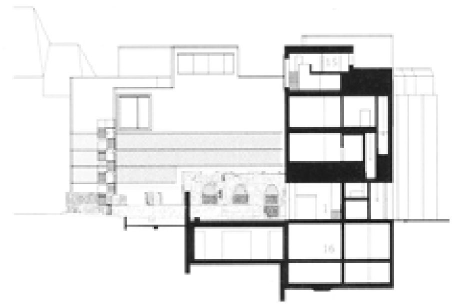

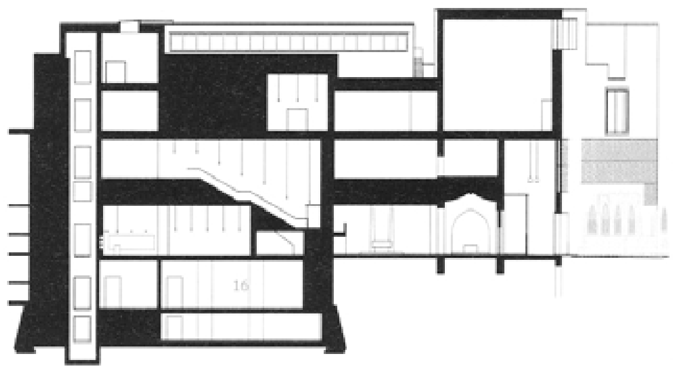

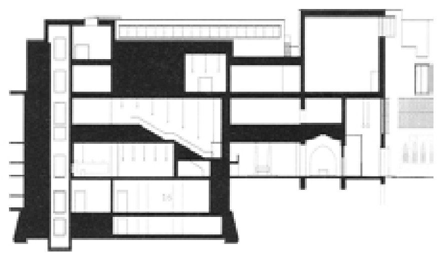

Saliceto Castle

Project data

Designer: Armellino and Poggio Architetti Associati
Location: Saliceto, Cuneo, Italy
Year of the intervention: 2011

Description

The project is the restoration of the Castle of Saliceto, near Cuneo, realized by Armellino and Poggio Architetti Associati. The architects conducted the architectural recovery of the castle and the insertion of multifunctional and exhibition spaces, to promote the permanent use of the building as a public space.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- disassembling

Scale of the intervention:

- technological unit
- **technological subsystem**
- **architectural system**

Classification of architecture elements:

- exterior walls
- roof
- interior wall
- interior floors
- **independent unit**

Materials:

- **dry**
  - stone
  - bricks
  - **wood**
  - **glass**
  - **metal**
- wet
  - concrete
  - mortar
  - clay

Design approach:

- **autonomy/dissonance**
- assimilation/consonance
- dialectical relationship/image reintegration

Technical complexities:

- **geometric constraints**
- production of customized units
- structural enhancement
- **compatibility of new materials with the existing building**
- level of detail of the new insertion
- color of the new insertion
- transportation costs
- long production chain of building elements
- **on-site assembly**

Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The medieval castle is located at the edge of the village of Saliceto. Its original structure dates back to the 13th century. Originally, its purpose was purely military-related. The building was surrounded by a moat and had a drawbridge, later replaced by a stone ramp. Towards the end of the 15th century it was modified and transformed into a noble residence, gradually losing its defensive characteristics and approaching the current architectural appearance. The structural and functional redevelopment of the building has included several phases of intervention, determined by the complexity of the building organism. First of all, the municipal offices were inserted. Then, public spaces such as reception rooms, multifunctional spaces, and conference rooms were created. The design foresees the use of new architectural and construction elements that maintain their recognizability alongside the pre-existence.

Characteristics of the technological system used

The design approach is autonomous, declared and legible. The new built volume has the grater architectural impact on the construction. This is the technological tower, which stands in its structural and formal autonomy from the context. The tower is composed by a steel structure and ventilated walls made of wooden panels.The panels are completely independent from the castle's curtain walls. The independency is emphasized through the insertion of glass plates connecting the new intervention with the pre-existence. The use of timber cladding determines an assonance of colors with the old materials, eliminating the insoluble philological problem of the reuse of ancient materials that create a camouflage. The design ensures architectural continuity between old and new. The shape of the new tower results from the identification of the geometric characteristics of the original volume.

Critical feedback

The project is a conservative act conducted respecting the authenticity of the Architectural Heritage and its complex stratification. The restoration intervention is a representative example of reintegration of the architectural wall gap, consisting of one of the four original towers, with a contemporary language. The resulting new volume recalls the original shape, through figurative autonomy.

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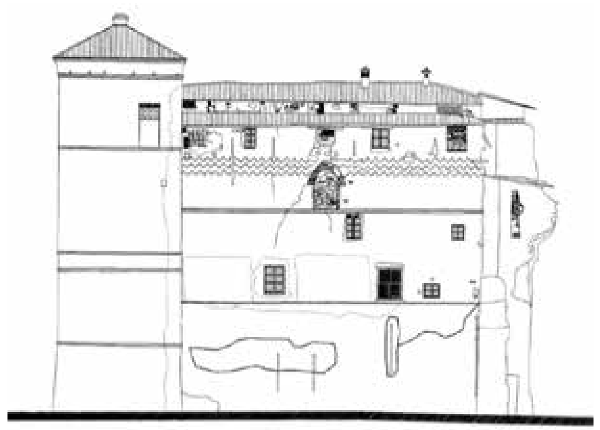

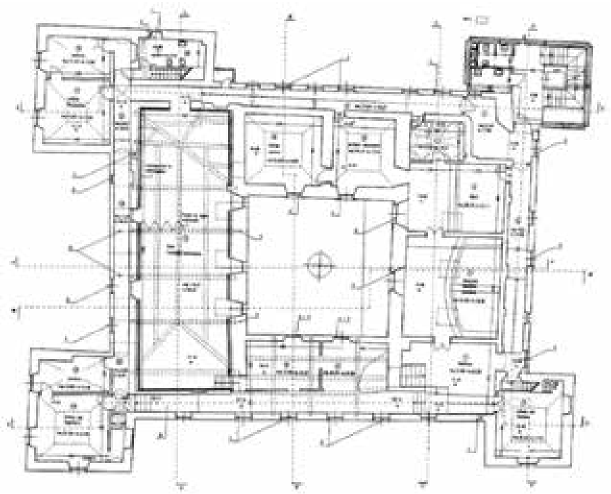

Bofilla Tower

Project data

Designer: Fernando Vegas and Camilla Mileto
Location: Valencia, Spain
Year of the intervention: 2011

Description

The Bofilla Tower is one of the oldest buildings in Spain, with over 800 years of history behind it. The architecture is 20 meters high. It is a clay construction. Its state of decay required a conservative restoration and the enhancement of the entire surrounding archaeological site.

Case of damage:

- **volumetric losses**
- **wall gaps**
- **damaged fragments**
- disassembling

Scale of the intervention:

- technological unit
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- roof
- interior wall
- **interior floors**

Materials:

- **dry**
  - stone
  - bricks
  - **- wood**
  - glass
  - **- metal**
- **wet**
  - concrete
  - mortar
  - **- clay**

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- production of customized units
- **structural enhancement**
- **compatibility of new materials with the existing building**
- **level of detail of the new insertion**
- **color of the new insertion**
- transportation costs
- long production chain of building elements
- **on-site assembly**

Typology of intervention:

- monolithic
- discretized
- **mixed**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The restoration of the tower served to establish the narrative potential of the architectural system. Before the intervention, the tower risked a collapse because of its state of abandonment and the low chemical-physical performance of its materials. The clay-based surfaces, subject to erosion and abrasion, needed integration and consolidation. A preliminary study of the state of conservation was followed by numerous recovery works, such as the cleaning of the façades, the reconstruction of the crowning, the reintegration of the entrance, the filling of the gaps both inside and outside the tower, and the insertion of an internal staircase leading to the top of the tower.

Characteristics of the technological system used

The architects maintained the original materiality of the rammed earth. The intervention had to take into account the following issues: general erosion of the surfaces, existence of a wall gap in the façade, disappearance of the original portal, disappearance of the historical wooden floors and parapets, degradation of the tower's roof, and dirt. Once the cleaning of all surfaces was completed, the missing parts were reintegrated by observing the original colour of the historical surface. Hydraulic lime mortar was used to harmonize the reintegrated gaps. The architects used local gravel and collapsed fragments. They inserted successive layers of stone, slightly recessed form the outer surface. Before filling in the gaps it was necessary to insert corrugated glass fibre rods to ensure the stability of the added volume. The staircase and interior floors are defined by a light weight metal and wood structure.

Critical feedback

The re-integrative approach is similar to the Roman rigatino technique in historical paintings. The challenge faced during the conservation process was, first of all, to reconcile the needs deriving from the progressive deterioration of the tower with the particularity of its material and construction technique. In addition, the need to preserve the historical and cultural authenticity of the materials and the original construction procedures, respecting the requirements of compatibility, distinctiveness, reversibility, and durability of the intervention, in order to preserve the character of the building.

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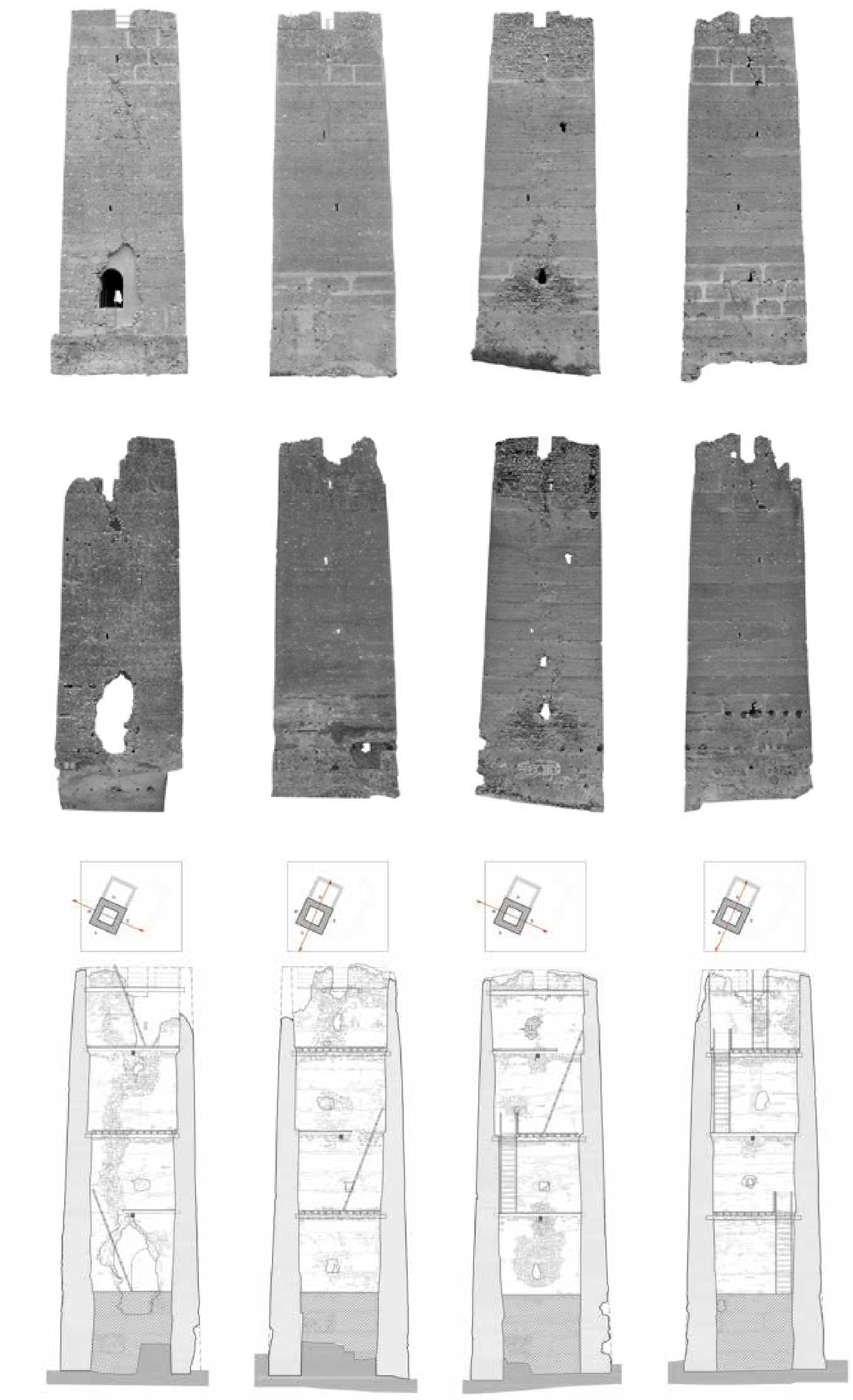


Bagrati Bathedral

Project data

Designer: Andrea Bruno
Location: Bagrati, Georgia
Year of the intervention: 2012

Description

The Cathedral of Bagrati is an important example of Georgian medieval architecture. An older restoration dates back to 1952 but the project by Andrea Giordano in 2012 gave the cathedral prestige and international exposure.

Case of damage:

- **volumetric losses**
- **wall gaps**
- **damaged fragments**
- **disassembling**

Scale of the intervention:

- technological unit
- technological subsystem
- **architectural system**

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

dry
- stone
- bricks
- wood
- **- glass**
- **- metal**

- wet
  - concrete
  - mortar
  - clay

Design approach:

- **autonomy/dissonance**
- assimilation/consonance
- dialectical relationship/image reintegration

Technical complexities:

- **geometric constraints**
- **production of customized units**
- **structural enhancement**
- **compatibility of new materials with the existing building**
- level of detail of the new insertion
- color of the new insertion
- **transportation costs**
- **long production chain of building elements**
- **on-site assembly**

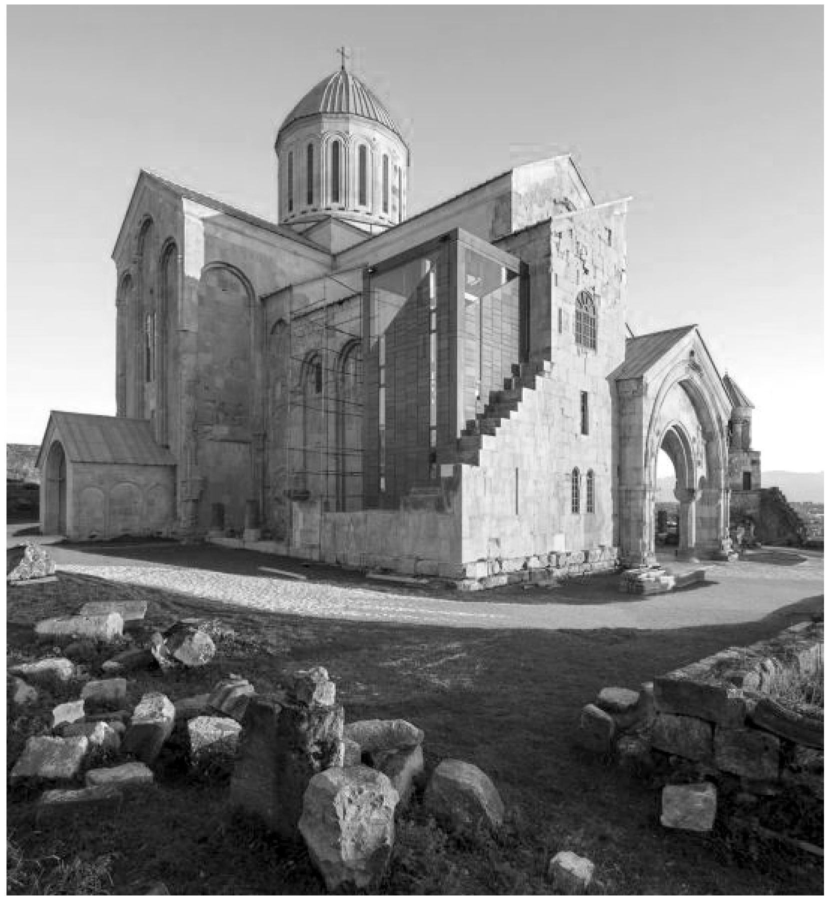
Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The 11th century Dormition Cathedral, known as Bagrati after the name of its founder, is located in the Georgian town of Kutaisi which was a religious and cultural centre in the 11th century. The cathedral of Bagrati has a cruciform plan with a central dome and an elongated western wing. On the sides of the main eastern apse there are two-storey chambers. On the second floor of both sides of the western arm there are galleries. From 1555, western Georgia became part of the Ottoman Empire with disastrous consequences for the building. The cathedral was sacked and bombed in 1692 and the dome, the drum, and the vaults were destroyed. In 1740, the cathedral was used as a military depot. In 1770, Russian soldiers took Kutaisi and kept the area besieged, subjected to gunfire and war actions. Before Andrea Giordano's intervention, several conservative restorations were realized. Both in the 1930's and the 1990's, the projects carried out were pure camouflage reconstructions, as the "where was it as it was" approach dictates. The architect was responsible for re-functionalizing the volume through contemporary additions.

Characteristics of the technological system used

The restoration consists of a large and complex project. The remains of the cathedral appear as a disorderly stratification of historical layers. To make the contemporary addition explicit, Andrea Bruno added a volumetric addition, where the building had collapsed, differently from its original shape. This volume, which contains the vertical connections, is made of steel and glass. Inside, the structural consolidation of the building is entirely made of steel, including the new vaulted system.

Critical feedback

The conservative attention is combined with consistent architectural quality: the methodological direction of the architect Andrea Bruno has radically changed the approach of the previous intervention, re-proposing the original volume with contemporary shapes and materials in an articulated relationship between old and new. The new intervention is also symbolic. It contrasts the stylistic mimesis of traditional architecture, denying that kind of approach.

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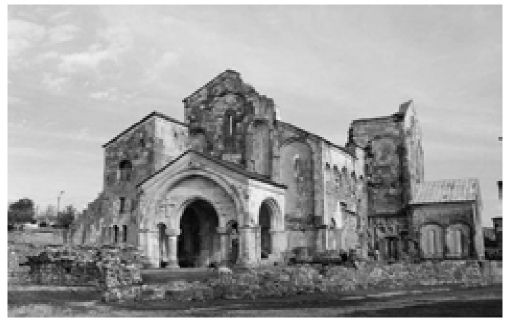
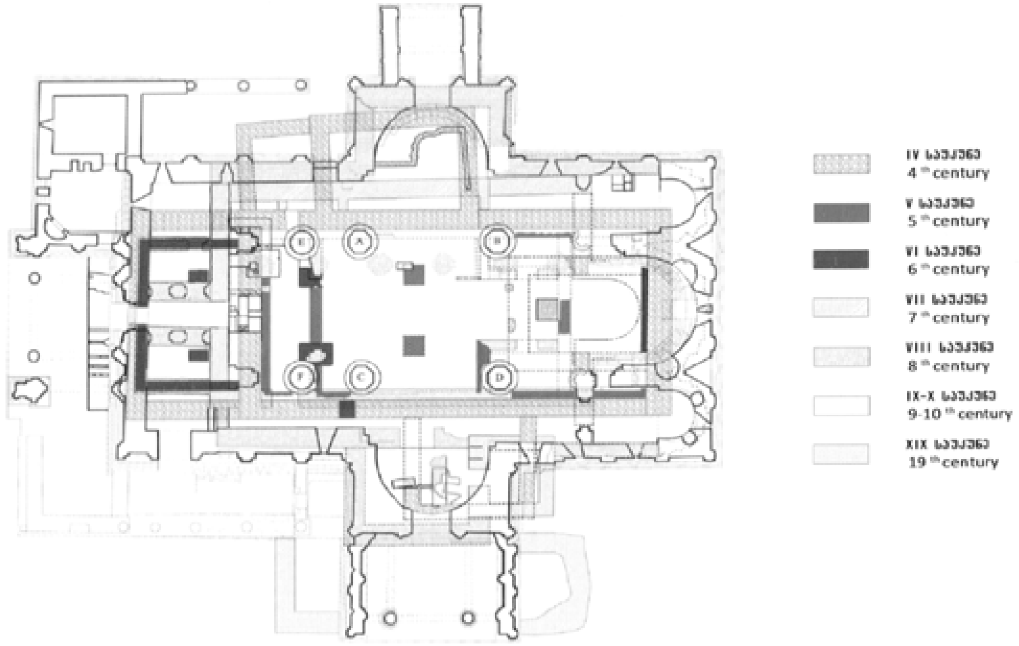




Monastery of Santa Catalina of Badaya - Santa Catalina botanical garden

Project data

Designer: Isuuru architects
Location: Sierra de Badaya, Alava, Spain
Year of the intervention: 2013

Description

The project consists in the consolidation of the ruins of the ancient Monastery of Santa Catalina de Badaya, situated in an archaeological site from the Roman period. The architects rebuilt slits and windows, according to the shapes that existed before. The architectural solution is simple and clean. They chose to use pine wood panels, which help to understand the formal unity by clarifying the chronology of the work.

Case of damage:

- **volumetric losses**
- **wall gaps**
- **damaged fragments**
- **disassembling**

Scale of the intervention:

- **technological unit**
- technological subsystem
- architectural system

Classification of architecture elements:

- **exterior walls**
- roof
- interior wall
- interior floors

Materials:

- **dry**
  - stone
  - bricks
  - **wood**
  - glass
  - metal
- wet
  - concrete
  - mortar
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- **production of customized units**
- structural enhancement
- compatibility of new materials with the existing building
- level of detail of the new insertion
- **color of the new insertion**
- transportation costs
- **long production chain of building elements**
- **on-site assembly**

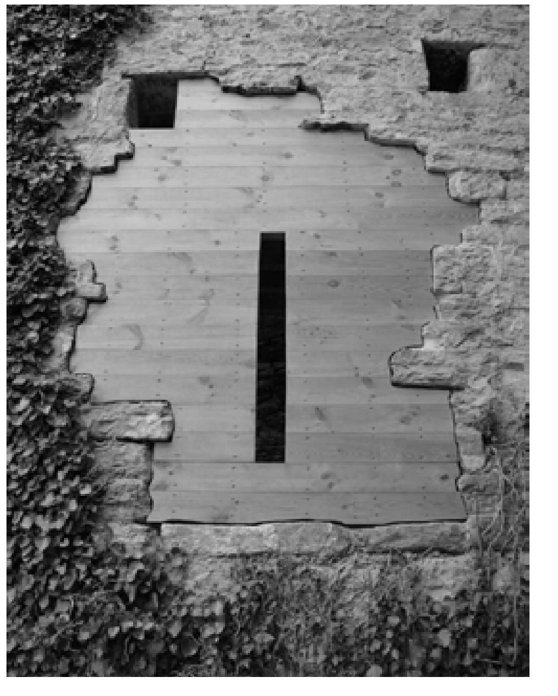
Typology of intervention:

- monolithic
- **discretized**

- **structural**
- **non-structural**
- mixed

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The monastery of Santa Catalina of Badaya is an example of Archaeological Heritage. The monastery lost the roof and, before the restoration, had significant volumetric gaps. The monastery was built between the 13th and 15th centuries. Its history has gone through several phases. The building was used in the 14th century as a convent and later as an Augustinian monastery. In the 19th century, it was set on fire during the first Carlist war. The state of degradation under which the building reached the present day derives form these events. The restoration work focused on cleaning the building and closing the gaps in the envelope, which was carried out using a contemporary language in contrast to the pre-existence. Before that, the architects of the Isuruu studio consolidated the envelope and secured the unsafe parts.

Characteristics of the technological system used

The restoration involved the consolidation of the wall gaps, the reconfiguration of the shape of the openings (windows, slits) into their original geometry (lost in disruption), and the structural consolidation of particularly damaged areas. The theme of the gap was addressed through the design of wooden pine elements. These elements were used to integrate the missing parts of the envelope. Where necessary, shoring was added to solve structural weaknesses. If geometry of the pre-existing hole was not known, the architects proposed the shoring with arbitrary standard profiles. All intervention were performed producing case-by-case customized dry elements and assembling them on site. The unity of image, finally, is limited to the remains of the monastery. The integrations are limited to the surfaces of the enclosure. The architects did not add building volumes.

Critical feedback

This case study brings together the main themes that the dissertation is interested in investigating. The key points are: the gaps in the envelope within complex geometric constraints, the contemporary language with which the project was approached, and the properties of the materials. The wood is suitable to be transported to the construction site and to be processed in sub-elements to compose complex geometries. This project also highlights the accuracy required in the different phases, from the dimensional survey of the gap, to non-standard construction, to installation. Today, the monastery is used as the monumental setting for a botanical garden. Because of the configuration of the castle, studies on the performance of the envelope were not needed.

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Baths of Diocletian, Aula Ottagona

Project data

Designer: Giovanni Bulian
Location: Rome, Italy
Year of the intervention: 2014

Description

The Aula Ottagona is a fragment of the ancient compound of the Baths of Diocletian in Rome, built between 298 and 306 A.D. by Massimiano. The architect Giovanni Bulian designed the most recent restoration by transforming some of the spaces of the Diocletian complex using a contemporary approach. As a result, modern structures dialogue with the pre-existence.

Case of damage:

- volumetric losses
- wall gaps
- **damaged fragments**
- **disassembling**

Scale of the intervention:

- technological unit
- **technological subsystem**
- architectural system

Classification of architecture elements:

- exterior walls
- roof
- **interior wall**
- **interior floors**

Materials:

- **dry**
  - **- stone**
  - - bricks
  - - wood
  - **- glass**
  - **- metal**
- wet
  - - concrete
  - - mortar
  - - clay

Design approach:

- **autonomy/dissonance**
- assimilation/consonance
- dialectical relationship/image reintegration

Technical complexities:

- geometric constraints
- production of customized units
- structural enhancement
- **compatibility of new materials with the existing building**
- level of detail of the new insertion
- **color of the new insertion**
- transportation costs
- long production chain of building elements
- **on-site assembly**

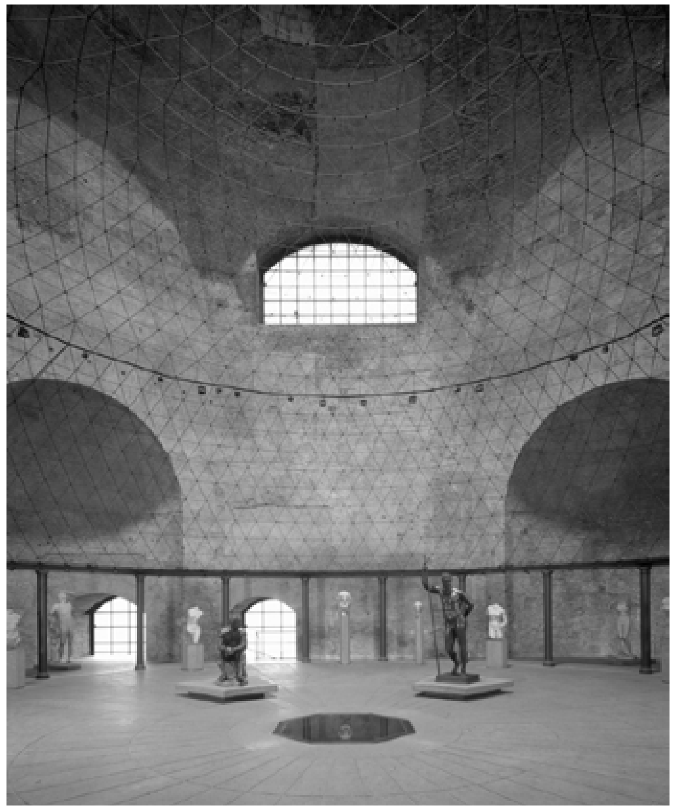
Typology of intervention:

- monolithic
- **discretized**

- structural
- non-structural
- **mixed**

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The Diocletian Baths, following their abandonment after the barbarian invasions of the sixth century AD, during the centuries have shown a predisposition to functional transformations, due to their morphological and constructive characteristics. In 1889 the Bath were used as National Roman Museum. From this moment, a process of enhancement of the monument began, which has continued to the present day. The project of recovery and functional adaptation involved various buildings of the compound, among which the Aula Ottagona that in 1911 was used as a gym and in 1929 as a planetarium.

Characteristics of the technological system used

The primary objective was to preserve integrally the monument, which witnessed the transition of history through the interventions carried out over time. Besides, the architect inserted new elements according to the logic of replaceability and reversibility. In the Octagonal Hall for example, a room that was chosen to display bronze and marble statues from the imperial baths of Rome, Giovanni Bulian decided to maintain the signs of the earlier transformations. For instance, he kept the triangular mesh of the geodetic structure of the former Planetarium, supported by 24 iron columns, which highlights the sense of unity of the space. The geodetic was deprived of the components necessary for the projection of the sky, allowing the view of the ancient dome that was previously prevented. Nearby, a metal staircase was built to reach the lower archaeological area. A path consisting of footbridges was designed. The new floors cross the rooms supported in some points by steel tie-rods tied to the top of the vaults. The pavement of the walkways consists of opaque and transparent areas. The latter, are used above artifacts.

Critical feedback

The restoration exalts the spacial unity of the Roman space through a moderate dialogue with modern structures. Their geometries animate, without overshadowing it, the centrality of the construction. The interventions are characterized by a strong design value in the restoration work. The monument was enhanced by creating an open museum system, without neglecting the enjoyment by the visitors along the exhibition path and nearby the pieces of art on display.

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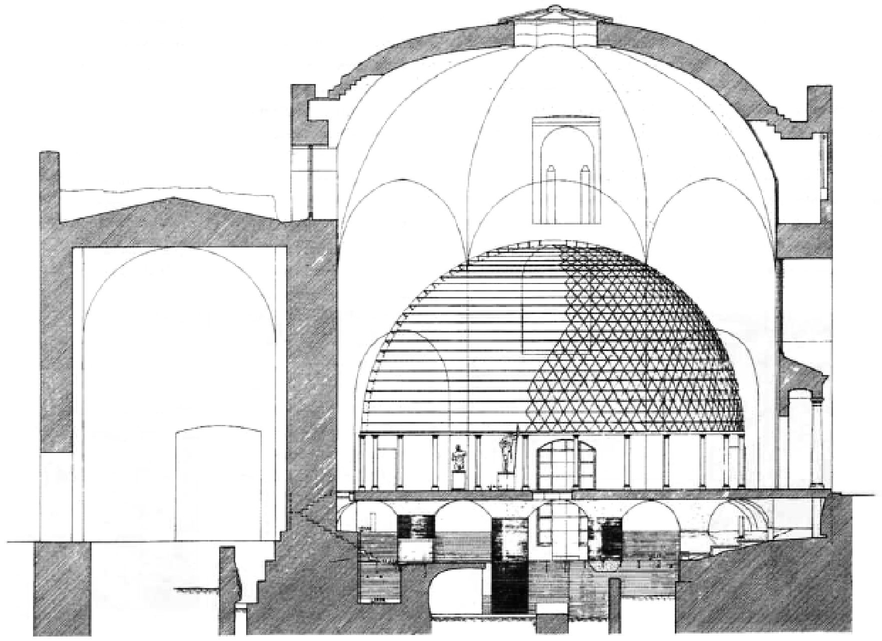
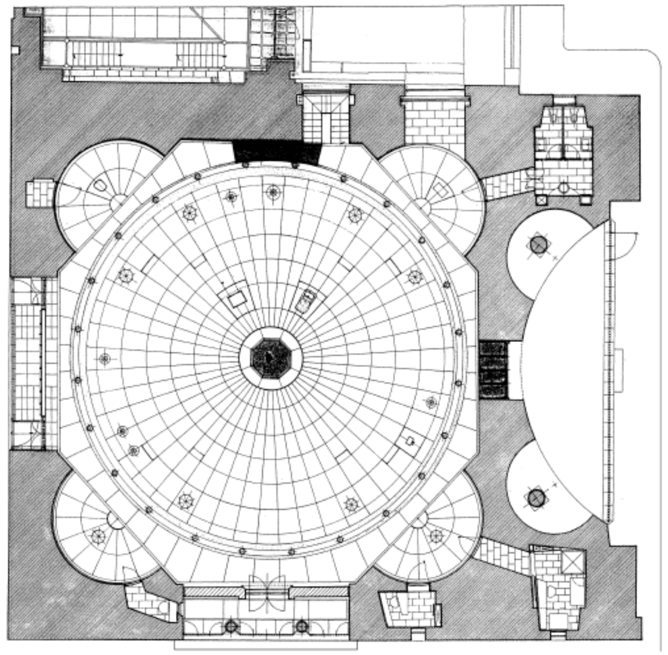




Setenil De Las Bodegas Homage tower

Project data

Designer: Fernando Visedo
Location: Setenil De Las Bodegas, Spain
Year of the intervention: 2014

Description

The tower of Setenil De La Bodegas is a landmark of the city. It was built during the Arab occupation, between the 12th and 13th centuries. It was a bulwark to defend the city and an obstacle to its conquest. The tower was abandoned in 1484, until its restoration in 2010 by the Spanish architect Fernando Visedo.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- disassembling

Scale of the intervention:

- **technological unit**
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

- **dry**
  - **- stone**
  - - bricks
  - - wood
  - - glass
  - - metal
- **wet**
  - **- concrete**
  - - mortar
  - - clay

Design approach:

- autonomy/dissonance
- **assimilation/consonance**
- dialectical relationship/image reintegration

Technical complexities:

- **geometric constraints**
- production of customized units
- structural enhancement
- **compatibility of new materials with the existing building**
- level of detail of the new insertion
- **color of the new insertion**
- transportation costs
- long production chain of building elements
- **on-site assembly**

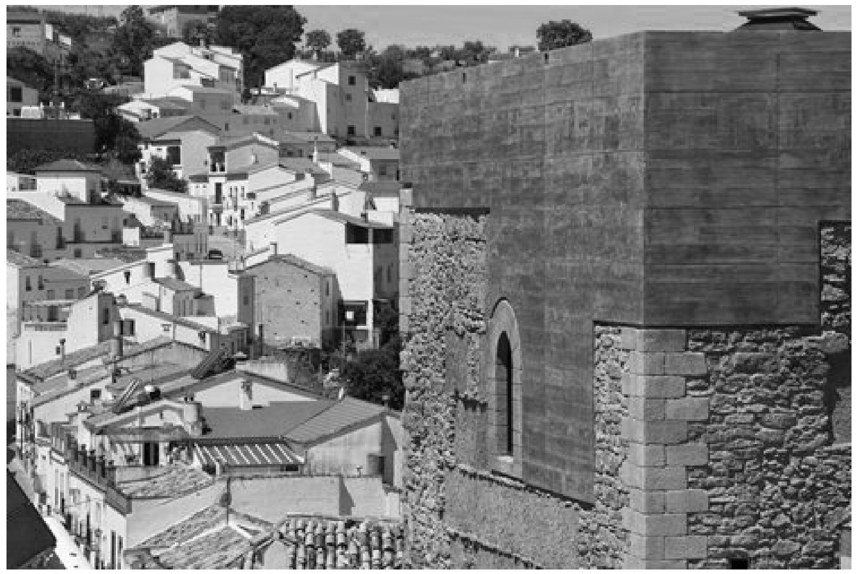
Typology of intervention:

- monolithic
- **discretized**

- structural
- non-structural
- **mixed**

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The tower object of intervention is the only one survived from the ancient fortress that protected the medieval city, together with the topographical conformation of the place. It has three floors. The first floor is covered with a barrel vault. It is accessible from the outer public space. The second floor is vaulted too. It is accessible by an external staircase. The third floor was the most deteriorated, due to the disintegration of the keystone of the vault that covered it. To make the monument accessible again, it was necessary to secure the structure and close the volume, which had been in the open air for five centuries.

Characteristics of the technological system used

The recovery of the tower is evident in the top floor. The restoration was carried out through the construction of a structural wall in reinforced concrete. The new wall was juxtaposed to areas where the original material was maintained, therefore putting alongside elements created by contemporary and historical techniques. The architect describes the entire intervention as the sum of the following design solutions: 1) creation of a wooden floating roof for the top of the building, with a color reminiscent of the tones of the fortress; 2) conservation of the interiors by cleaning and removing the layers that covered the original substrate. Consolidation of the historical support and creation of a homogeneous covering; 3) intervention on the façade by adopting the historical adobe technique (consolidation of mud and masonry to rebuild the original thickness); 4) combination of traditional masonry and concrete at the third floor; 5) homogenization of the color of the façade.

Critical feedback

The project is an articulated example that takes into account the reorganization of the interiors, the reconfiguration of the formal unity and structural consolidation. This dissertation addresses particular interest in understanding how the volumetric gap issues was solved. The missing volume, before the restoration, was consistent; it was at the scale of an architectural sub-system. The most damaged parts were reconstructed with contemporary technologies. In other areas, better preserved as they were originally, local vernacular construction techniques were used. This approach was applied both in the envelope and in the internal areas.

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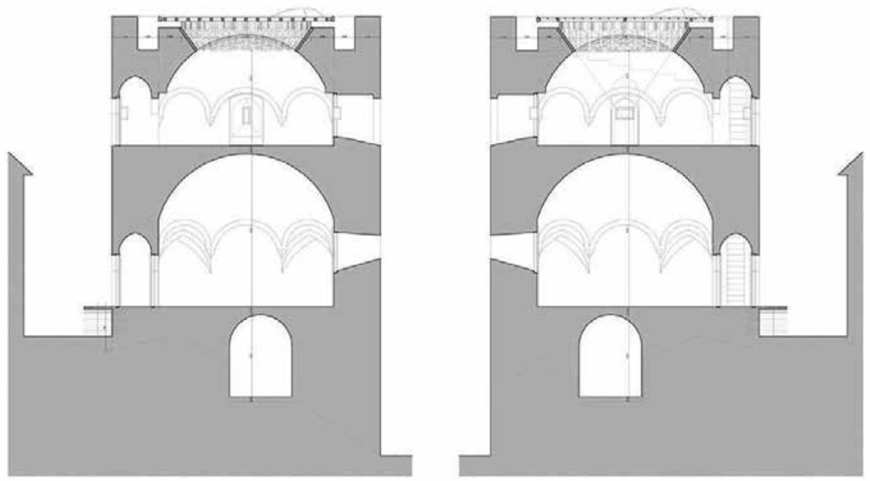

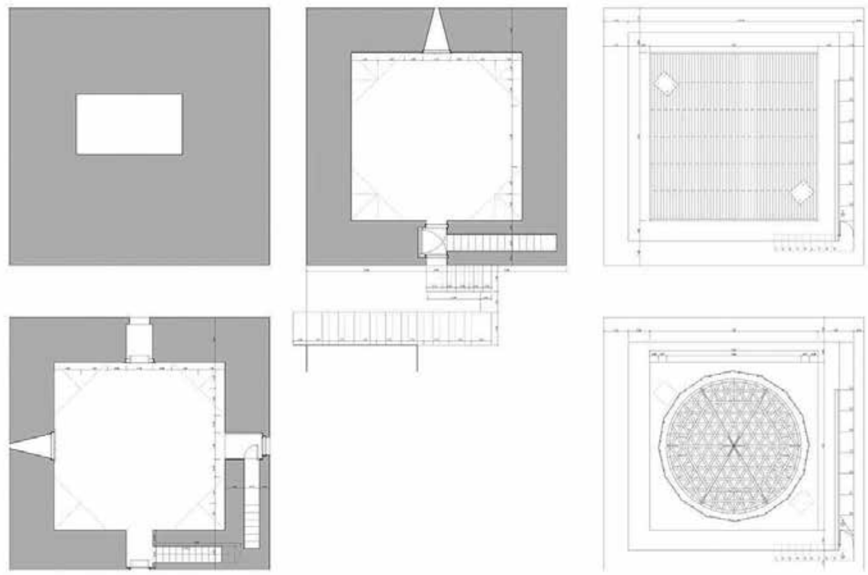

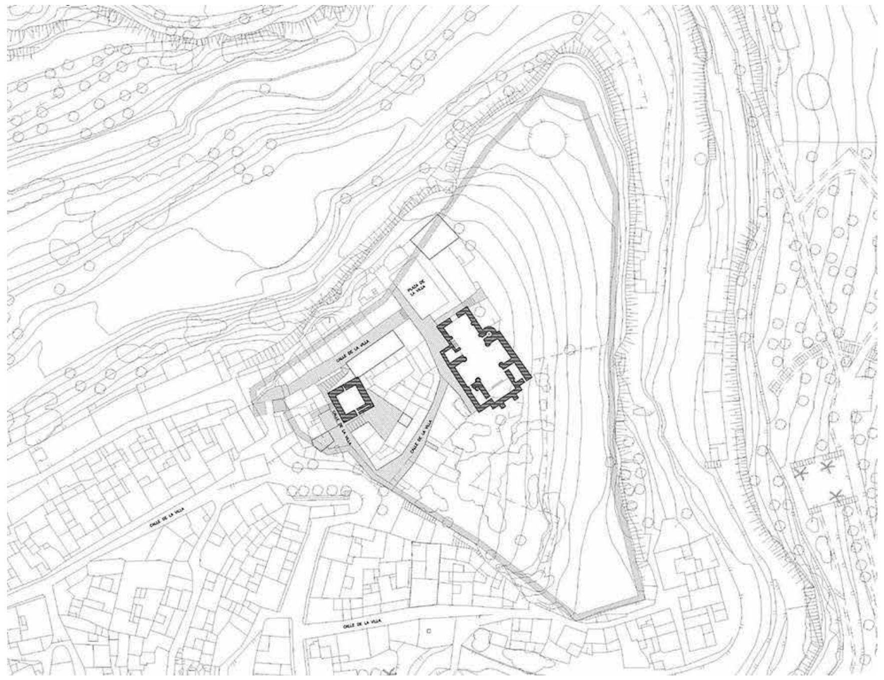

Fortezza medicea in Arezzo

Project data

Designer: De Vita and Schulze Architects
Location: Arezzo, Italy
Year of the intervention: 2015

Description

The Fortress of Arezzo is a 16th-century fortified complex designed by Giuliano and Antonio da Sangallo the Elder, completed by Antonio da Sangallo the Younger. The restoration of the monument served to consolidate the walls and recover the inner spaces to be used for new functions.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- disassembling

Scale of the intervention:

- technological unit
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- roof
- interior wall
- interior floors

Materials:

- **dry**
  - stone
  - bricks
  - **wood**
  - glass
  - metal
- wet
  - concrete
  - mortar
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- **production of customized units**
- structural enhancement
- compatibility of new materials with the existing building
- level of detail of the new insertion
- color of the new insertion
- transportation costs
- **long production chain of building elements**
- **on-site assembly**

Typology of intervention:

- monolithic
- **discretized**

- structural
- non-structural
- **mixed**

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The fortress showed signs of degradation in the ramparts, which were mined in 1800 by Napoleon's troops. The restoration included the consolidation of the stone walls, the reorganization of the interior spaces to make them accessible, the technological requalification, and the redesign of the system of pedestrian accesses and routes, to bring back into the Fortress cultural activities. In addition to specialist restorations, functional and architectural additions were added with a consistant search for the dialogue between old and new. This dialogue is necessary for a critical understanding of the monumental complex, which includes metal bridges, elevators, stairs, and stages.

Characteristics of the technological system used

In this project, it is relevant the approach to the reconstruction of one of the completely destroyed ramparts. The missing perimeter wall was replaced with a light wooden structure composed of horizontal battens. The laths are long enough to define the original curvilinear shape. At the interface with the pre-existing structure, the laths were shaped in such a way as to fit precisely with the disjointed geometry of the original stone. This result was achieved thanks to a meticulous design and the elaboration of a unique and unrepeatable contemporary volume.

Critical feedback

The restoration of the Medici fortress in Arezzo is representative of an approach open to the contemporary and to the transmission to the future of a monument that incorporates signs of different eras. It would have been possible with less effort to integrate the missing volume with a stone masonry. Instead, it was decided to customize construction elements that in the culture of contemporary design have instead standard size ranges. When analogies between traditional design processes and the future of automation are suggested, case studies like the one analyzed are particularly significant. Automating the geometric definition of architectural units, considerably lengthens the time that can be devoted to optimizing the project.

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Matrera castle

Project data

Designer: Carquero Arquitectura studio
Location: Villamartìn, Spain
Year of the intervention: 2015

Description

The castle of Matrera is an Andalusian fortress built in the 9th century. It was restored by the Carquero Arquitectura studio. The intervention consists of a structural consolidation of the ruins and the completion of the volume, on the trace of the original shape, recognizable by the pre-existing fragments.

Case of damage:

- **volumetric losses**
- **wall gaps**
- **damaged fragments**
- **disassembling**

Scale of the intervention:

- **technological unit**
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- roof
- interior wall
- interior floors

Materials:

- **dry**
  - **stone**
  - bricks
  - wood
  - glass
  - metal
- **wet**
  - **concrete**
  - **mortar**
  - clay

Design approach:

- autonomy/dissonance
- assimilation/consonance
- **dialectical relationship/ image reintegration**

Technical complexities:

- **geometric constraints**
- production of customized units
- structural enhancement
- **compatibility of new materials with the existing building**
- level of detail of the new insertion
- color of the new insertion
- transportation costs
- long production chain of building elements
- on-site assembly

Typology of intervention:

- monolithic
- discretized
- **mixed**

- **structural**
- non-structural

Durability of intervention:

- temporary
- **permanent**

Performance requirements of the project

The restoration of the castle of Matrera by the Carquero Arquitectura studio is an example of the recomposition of wall fragments through the integration of missing areas with discrete elements, recovered from the ruins themselves. The ruins consist of blocks of limestone. They were subsequently covered with lime-based plaster, similar to the one that initially characterized the envelope, to highlight the contemporary design intervention. With criteria of compatibility and authenticity, the intervention aims to structurally consolidate the elements at risk. The additions were differentiated from the original structure. Mimetic reconstruction was avoided. The project aim was to recover the volume and tone that the tower originally had as a landscape icon.

Characteristics of the technological system used

The approach consists in the restitution of the figurative unit of the work, through the treatment of the gap as a technological unit. The degradation of the monument was defined by the collapse of the limestone. It was reused to restore the buttresses and reinforce the structure. The upper part of the building was rebuilt to make the thin residual wall, in danger of collapse, more solid. It also recalls the original battlements. The reconstructions are functional to the re-proposing of the formal unity. The geometry of the original volume is enhanced by the uniform covering in lime mortar.

Critical feedback

The language of restoration is explicit. The contemporary intervention has the function of volumetric reconfiguration and structural consolidation. It seems that the fragments cling to the new perimeter wall. It is interesting to note that the gap is not in this case a missing volume within a wall constraint. The gap surrounds the fragments and is treated to extend the damaged limits of the envelope towards a completed form. The reuse of the rubble has served to resolve part of the question of material compatibility. The interaction with the pre-existing irregular geometry was addressed through a vernacular construction method. The project served to convey a monumental landmark to the future. It was not necessary to address the performance of a closed volume, as the Matrera Castle will continue to exist in its geometric incompleteness.

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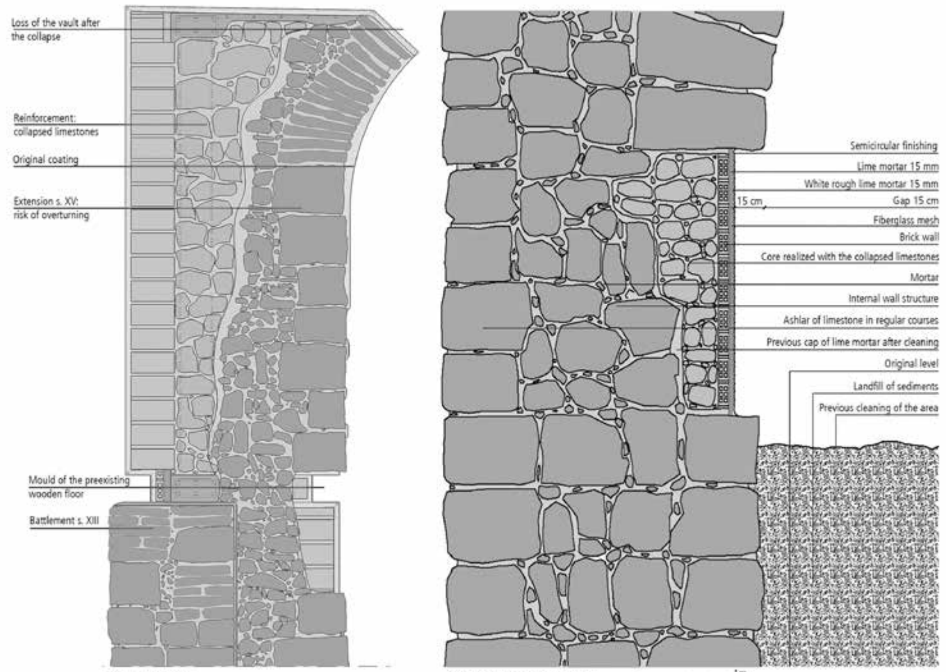


Detail of the crown

Detail reinforcement of the wall

Vilanova de la Barca's church

Project data

Designer: AleaOlea architecture and landscape, Baldomer Ric
Location: Vilanova de la Barca, Spain
Year of the intervention: 2016

Description

The Church of Vilanova de la Barca is a Gothic building from the 13th century, partially demolished in 1936 after the bombings during the Spanish Civil War. Since then, the church has been in a state of ruin and neglect, preserving only the apse, some fragments of the aisles, and the west façade. The main objective of the project was to recover the remains of the old church by transforming the old structure into a new multi-purpose hall.

Case of damage:

- **volumetric losses**
- **wall gaps**
- damaged fragments
- **disassembling**

Scale of the intervention:

- technological unit
- **technological subsystem**
- architectural system

Classification of architecture elements:

- **exterior walls**
- **roof**
- **interior wall**
- **interior floors**

Materials:

- **dry**
  - stone
  - **bricks**
  - wood
  - glass
  - **ceramics**
- **wet**
  - concrete
  - **mortar**
  - clay

Design approach:

- **autonomy/dissonance**
- assimilation/consonance
- dialectical relationship/image reintegration

Technical complexities:

- **geometric constraints**
- production of customized units
- **structural enhancement**
- **compatibility of new materials with the existing building**
- **level of detail of the new insertion**
- **color of the new insertion**
- transportation costs
- long production chain of building elements
- **on-site assembly**

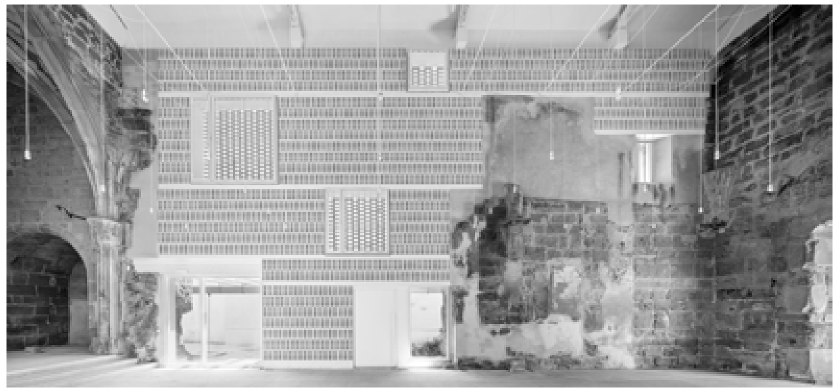
Typology of intervention:

- monolithic
- **discretized**

- **structural**
- non-structural
- mixed

Durability of intervention:

- temporary
- **permanent**



Performance requirements of the project

The 13th century church in the village of Villanova de la Barca after the war was left as a ruin. The restoration was necessary to restore the form and adapt the building to a new function. It is no longer a place of worship, but a social and cultural centre. The surviving stone walls of the old church have been stabilized and consolidated. They provide the framework for the restoration of the missing walls and roof with new materials, thus recovering the spatial qualities of the original church. The new work was made with materials and details deliberately different from those of the original surviving building.

Characteristics of the technological system used

The main part of the project concerns the facade and the roof. The restoration consists of a new brick façade based on a trellis structure and a new gabled tile roof. The system is conceived as a new ceramic architectural shell that leans on the remains of the ancient building. The exterior façade is windowless. The surface is texturized. The texture dialogues with that of the stone ashlars of the old church. This promotes visual continuity and integration with the original architectural system. The interior façade is made by perforated white bricks that reinforces the contrast and discontinuity between the old and the new. The new roof consists of clay slabs supported on a simple and detailed steel structure, which incorporates thick insulation, supported in turn by steel trusses. From the outside, the contemporary intervention is minimal and focuses on the formal reconstruction of the volume. From the inside, the restoration has a greater stylistic and aesthetic autonomy.

Critical feedback

During the renovation of the church, the architects of AleaOlea used a lightweight structure consisting of a staggered arrangement of white bricks laid on the original ashlar walls. The old and the new structure dialogue harmoniously. This relationship redefines the sacred place according to the new functional characteristics. The restoration is both disruptive and respectful of tradition. The arrangement of the interior spaces opens up to the themes of interior design. The project also includes scenic elements such as the carpeting vegetation, which designs a threshold space between exterior and interior. The strength of this project lies in having reinterpreted the use of traditional materials with a language that approaches the aesthetics and historical building tradition with autonomy.

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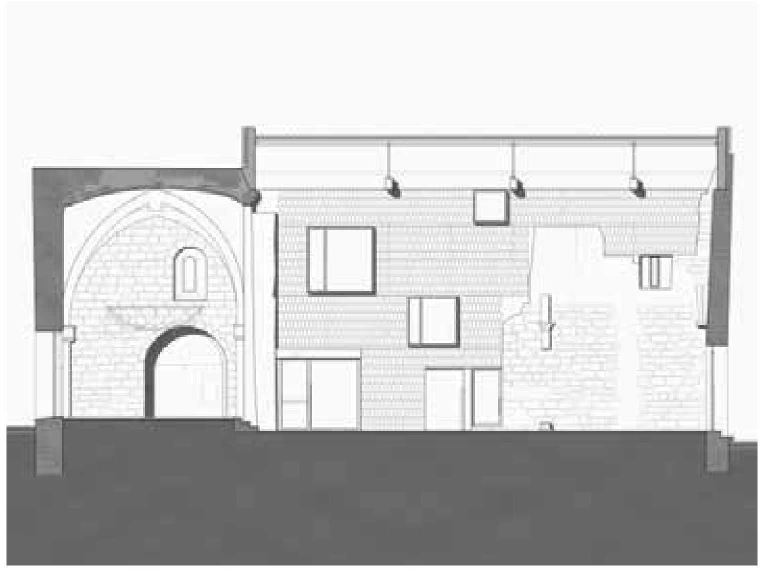
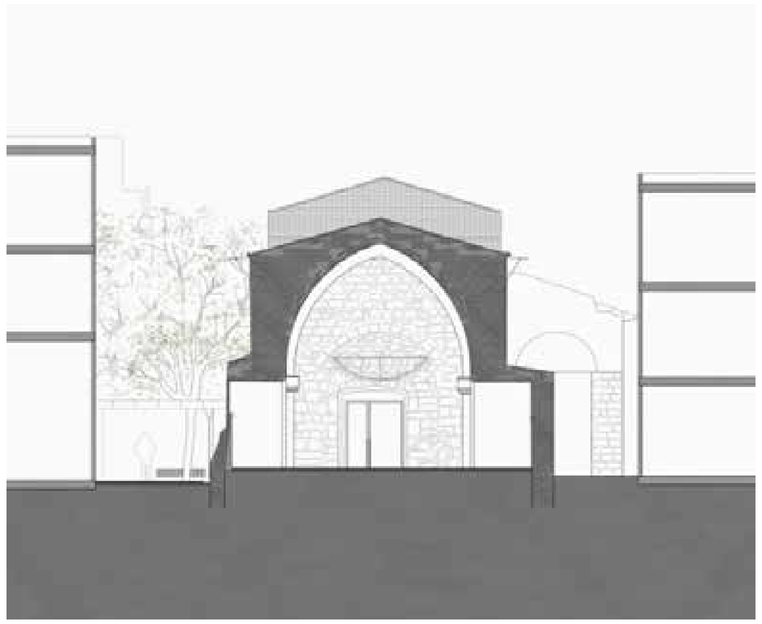
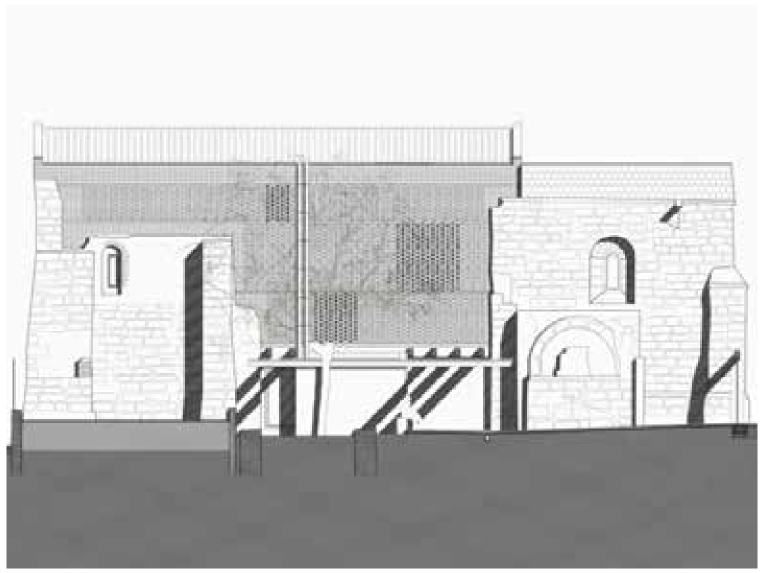






5.1.4 Operating tools deriving from the analysis of case studies

The analysis of case studies was used to determine some technical complexities that emerged particularly in the production phase of the elements necessary for the materialization of the project. As Maria Luisa Germanà observed in "Scheduled maintenance of archaeological sites" (a concept that can also be extended to architectural heritage) the construction site can be discretized according to low and highly complex technical interventions. Interventions with low technical complexity "can be performed with a few simple tools" assuming an almost daily presence on the site and "an organization of maintenance activities more related to the single site that are configured above all as preventive actions". On the other hand, highly complex technical interventions "involve highly specialized design and execution skills, with the use of sophisticated equipment and techniques. In this case "we can envisage a centralized management, involving more sites and creating the conditions for economies of scale, for the execution of maintenance interventions of greater financial commitment" (Germanà and Sposito, 2001).

These technical needs can be addressed through the use of innovative tools, bearing in mind that:

- the Fourth Industrial Revolution is leading to the ubiquity of digital fabrication tools in the production sectors. The flexibility of digital fabrication overcomes the limits of mass production towards mass customization. These machines can use any tool that laborers use with greater precision and speed. Moving from mass production toward mass customization occurs by progressively shortening the phases of the entire design chain, from the conceptual phase to the construction phase;
- digital design and release from standard production methods is opening up various possibilities in terms of spatial transformation and engineering of new materials;
- the use of parametric tools is increasingly widespread to identify and quantify in advance the complexities that can arise in the production phase of buildings;
- the use of robots in architecture allows the prefabrication of elements with saving in labor and material costs;
- the growing awareness of the limits of natural resources (Meadows et al., 2014) and that the Anthropocene will have irreversible consequences as a result of technological development (Crutzen, 2006), leads to an exaggerated attention to sustainability issues and the circularity of resource (Lacy and Rutqvist, 2016) that can be pursued with careful control of the processes.[44]

44 These changes are progressively breaking down the innovation barriers that two decades ago were identified by Carlos Balaguer as "open issues in the EU construction automation" as: 1) high cost of the robotic system, which according to data provided by the International Federation of Robotics are falling, on average, from 100,000 euros in 1991 to 60.000 euros in the 2000s (also thanks to the constant diffusion of industrial robots); 2) high sophistication of the robot control system, which is now bing overcome through the democratization of operating tools, programming interfaces and CAD-CAM communication systems; 3) processing with a reduced range of materials, now undergoing research and development in the academic field; 4) the necessity of using special parts, i.e. the impossibility for construction site robots to work with low cost standard parts (instead of sophisticated grippers or new mortar application methods), which is now being overcome thanks to the possibility of introducing in the production chains the possibility of mass production in a customized way.

This research responds to the needs of the traditional construction site by assuming the use of industrial robots directly on-site. As generic machines, robots can perform any type of programmed action, through additive, subtractive and training processes. Given the genericness of robots, attention is directed toward operational specificity, determined through the installation of the end-effector, able to perform additive manufacturing operations. Among the reasons for this choice is the fact that additive production is a key procedure for reducing the production chain of the elements on site. Secondly, additive production represents a potential technology capable of updating the business models in the construction sector as it is already happening in design.

In order for this change to be possible, there are complexities to be resolved at macro-scale, such as: 1) the still high cost of automated systems in relation to the cost of traditional systems to perform the same operation; 2) the reduced sensory and cognitive capacities of robots 3) the lack of a boundary infrastructure that allows a management of dimensional tolerances to carry out work on-site 4) the lack of a European regulatory framework that manages the transport operations of the machines on-site and site safety. In parallel, it is possible to identify technical complexities that can be solved in a research laboratory environment. In this way it is possible to contribute to the advancement of technology and push the technology readiness level from the validation of the academic tools to the validation in a commercial / industrial environment.

There are still no robotic additive manufacturing experiments on-site on existing buildings. Based on the current state of the art progress, technical complexities have been formulated that have not yet been validated at the research level.

In order of priority:

- control of the robot's working space in relation to the target points to be reached;
- possibility of making the ALM process interact with irregular horizontal and vertical surfaces;
- control of dimensional tolerances;
- control of the detail level of the project outcome;
- color control;
- definition of a wide range of engineered materials (potentially also customizable based on local resources) that have bearing capacity for interventions that are temporary or permanent;
- development of robotic computer vision technologies through feedback loop sensors in a dynamic environment (modifications, crashes, cleaning that are performed directly on-site at the architectural pre-existence).

On the basis of these elements the research structured a laboratory experiment that aimed at solving certain complexities that may be useful to start up consequent research activities. Verification was part of the feasibility study of the process (Pizzi, 2013), which was structured into:

1) project preliminary analysis;
2) technical feasibility;
3) environmental compatibility;

4) financial sustainability;
5) economic-social convenience;
6) procedural verification;
7) risk analysis.

The limit that surely emerges, independently of the additive production technology employed, of the deposit of material on a leveled horizontal plane. Working on the existing instead requires greater degrees of freedom, both in terms of irregular starting surfaces and with different inclinations, as well as the adaptation of the project during the construction phases.

To make the search more aware also in terms of the results expected to be achieved, an ideal workflow of robotic ALM on the CH[45] is formulated below. This tool will allow, on the one hand, to check procedures and methods for depositing material on uneven surfaces in a controlled environment, as well as helping to increase the level of digital documentation of the intervention on the existing, guaranteeing the possibility of project adaptation on-site and opening up to possible scenarios of industrialization on-site and off site. At the conclusion of the laboratory experiment, a comparison will be made between laboratory workflow and hypothetical on-site workflow to take stock of current technology readiness level and future possibilities.

45 Digital Fabrication Techniques for Cultural Heritage: A Survey, in *Computer Graphics Forum*: " The manufacturing industry has been the main domain of 3D printing applications over the last decade. Available at: http://vcg.isti.cnr.it/Publications/2017/SCPCD17/DigitalFabricationForCH.pdf. Digital fabrication techniques have also been demonstrated to be effective in many other contexts, including the consumer domain. The Cultural Heritage is one of the new application contexts and is an ideal domain to test the flexibility and quality of this new technology".

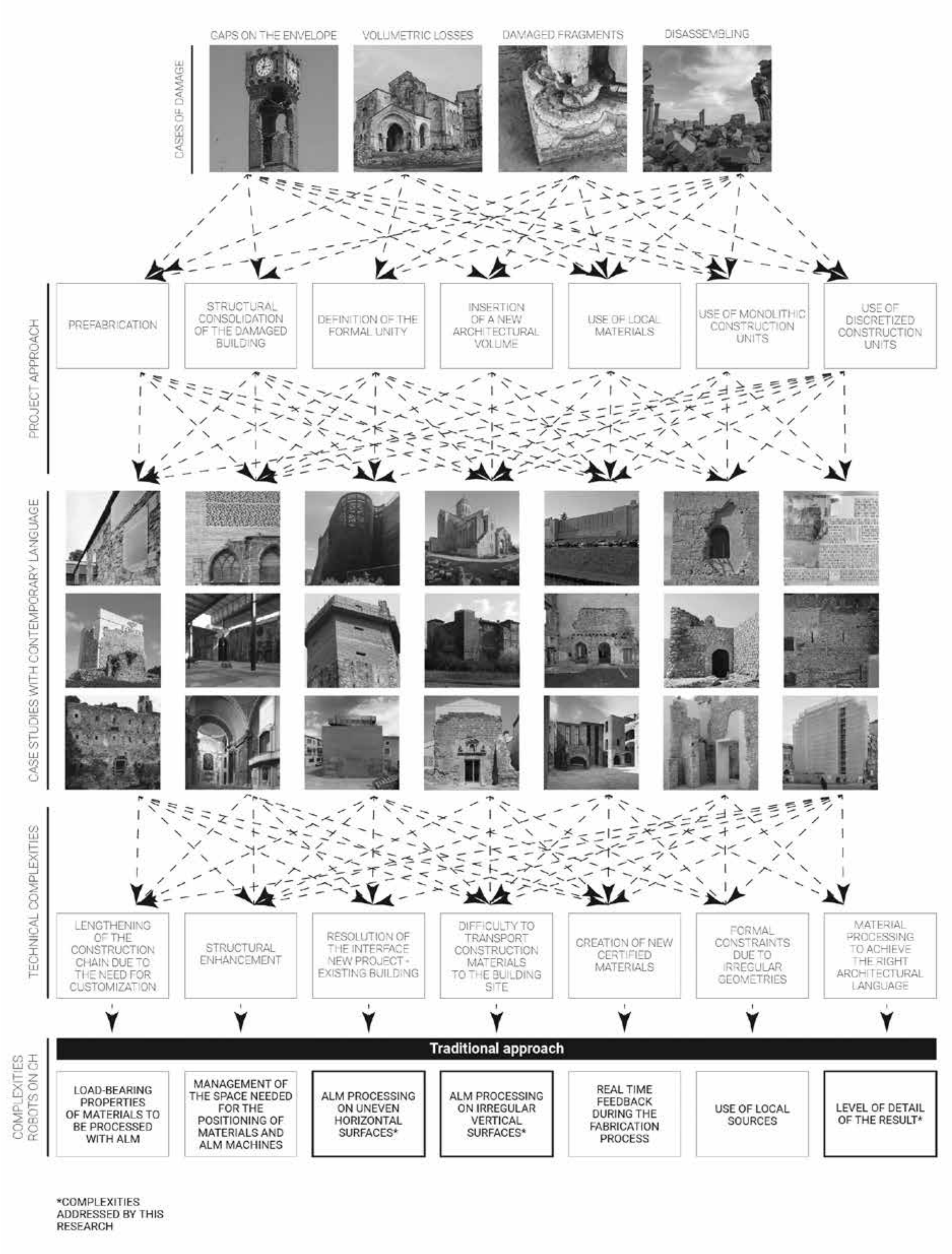


Fig. 5.1 Synoptic diagram resulting from the analysis of the case studies. Direction of the doctoral research towards an experimental application, through the identification of the technical complexities that take place in the project workflow.

5.2 Robots

"The machine of a thing and the material wants to do another. So many of our experiments are wrestling with or negotiating between these two conditions [Monica Ponce de Leon, 2017]

5.2.1 Project selection criteria

Robotic digital fabrication allows for the exploration of new production methodologies that connect parametric computational process directly to material. The exploration of the state of the art aims to direct this research towards a laboratory experimentation that puts robotics and cultural heritage in relation to one another. The technologies that can be included in the recovery processes of damaged architecture already have a wide field of application for surveying and diagnostics. This chapter illustrates the possibility of using innovative new tools to engage the on-site production chain.

In order to define appropriate work premises for the experiment hypothesis, automated tools were investigated that produced successful examples of technological systems or realized units. Most of these automated robotic tools reside in academic research. Today there are few examples of robotic or AM application to cultural heritage at the building scale (Calzolari et al., 2017). Despite this, it is possible to investigate procedural principles that facilitate a deepening of research in this direction. Therefore it is useful to analyze through a systemic approach a schedule of case studies that are representative of:

- execution of digital workflows ranging from decision-making phase to component production;
- exploration of digital craft and new formal codes through the materialization of digital models using digital manufacturing technologies (robotics, AM, or robotic-AM);
- the development of tools implemented by feedback loop systems that extend the sensory capacity of production machines through sensors that relate designer, machine and materials (robo-sensing) for on-site operations;
- the development of tools able to decode the human presence within the work area and to interact with the workers in the work phases (cobotics);
- the development of production procedures in relation to existing surfaces or in the presence of geometric limitations in the work area.

Sensors are useful and increasingly necessary for on-site construction processes as a means to monitor unpredictable changes or dynamic conditions. In the case of subtractive manufacturing or bricklaying systems, sensors allow the design output to be adapted to the geometry of the surrounding environment. In the case of additive manufacturing, the sensing technology allows the toolpaths to be updated based on the behavior of the deposited material. With increasing accuracy and reduction in cost of sensing technology, robots will be able to achieve greater potential and provide increased decision-making capability. These parameters were the primary selection criteria that made up the case study survey guidelines for the elaboration of the operational tools to set up the robotic-alm experiment.

5.2.2 Classification of projects

To hypothesize a correlation between architectural heritage and the use of robots, it is necessary to resort to the analysis of laboratory experiments aimed at advancing the state of knowledge in the sector. A large collection of research projects can be traced back to the series of publications *Rob | Arch (2012-14-16-18)* and *Fabricate (2011-2014-2017)*. The laboratory activities documented in these publications focus on the scalability of digital fabrication processes, mainly robotic, for architectural applications. These studies take place through the processing of different materials with subtractive procedures (wood, stone, metal), additives (concrete / ceramic / rammed soil-based, synthetic, and combined materials), assembly (elements discretized like bricks), or combined (metals , textile fibers). There are numerous recent explanatory examples of these technologies and they are listed below.

Subtractive manufacturing

These projects introduce processes for which the production of an outcome is defined by the subtraction of material from the starting volume. In terms of end-effector, reference is made to the use of spindles, hot wire cutters (RHWC), or chisels. One of the main explorations of this technology is digital stereotomy, making a connection to the historic methods used for cutting stone. For the restoration building site, applications can be envisaged for the on-site prefabrication of discrete or assembled components of the wood, stone, or ceramic type in the various variations. The programming of the chiselling robots can also be translated for interaction with frescoes or in work contexts where the precision of the machine compensates for human errors.

2012

Robotically fabricated wood plate morphologies, ICD Stuttgart: Achim Menges, Tobias Schwinn, and Oliver Krieg, 2012 (Schwinn et al., 2013);
Mill to fit, TU Graz: Andreas Trummer, Felix Amtsberg, and Stefan Peters, 2012 (Trummer et al., 2012);
Automating eclipse - automated robotic fabrication of custom optimized metal facade systems, Harvard GSD and Virginia Tech: Nathan King and Jonathan Grinham, 2012 (King and Grinham, 2013);
Robosculpt, Taubman College University of Michigan: Mathew Schwartz and Jason Prasad, 2012 (Schwartz and Prasad, 2012);
The framed pavilion, IAM Graz: Richard Dank and Christian Freissling, 2012 (Dank and Freißling, 2013).

2013

Meteorosensitive pavilion, ICD Stuttgart: Achim Menges et.al., 2013 (Krieg et al., 2013).

2014

Design and Fabrication of Robot-Manufactured Joints for a Curved-Folded Thin-Shell Structure Made from CLT, IBOIS Switzerland: Christopher Robeller, Seyed Sina Nabaei and Yves Weinand, 2014 (Robeller et al., 2014);
Performative tectonics, Tongji University: Philip F. Yuan, Hao Meng and Pradeep Devadass, 2014 (Yuan et al., 2014);
Geometry and performance innovation in ceramic building systems through design robotics, Harvard GSD: Stefano Andreani and Martin Bechthold, 2014 (Andreani and Bechthold, 2014).

2016

IBOIS and EPFL Lausanne: Christopher Robeller and Yves Weinand, 2016 (Robeller and Weinand, 2016)
Stereotomy of wave jointed blocks - University of Sydney: Simon Weir, Dion Moult, and Shayani Fernando, 2016 (Weir et al., 2016).

2017

FRP (fiber-reinforced polymer) composites for high-rise building facades, Kreysler & Associates: William Kreysler (Kreysler, 2017);
The Armadillo Vault, Philippe Block, Matthias Rippmann, and Tom Van Mele: ETH Zurich and Block Research Group: 2017 (Block et al., 2017).

2018

Versatile Robotic Wood Processing, Chiba University: Hiroki Takabayashi, Keita Kado, and Gakuhito Hirasawa, 2018 (Takabayashi et al., 2019);
Investigations on Potentials of Robotic Band - Saw Cutting in Complex Wood Structures, Tongji University: Hua Chai and Philip F. Yuan, 2019 (Chai and Yuan, 2019);
Altered Behavior: The Performative Nature of Manufacture Chainsaw Choreographies + Bandsaw Manoeuvres, AA School of Architecture: Emmanuel Vercruysse, Zachary Mollica, and Pradeep Devadass, 2019 (Vercruysse et al., 2019).

Additive layer manufacturing

Additive Layer Manufacturing (ALM) are processes that materialize complex morphologies by translating digital information into the physical environment. The ALM technologies able to sustain the leap in scale from the object to architecture are mainly of powder bed deposition (commonly known as 3D printing) or that of robotic extrusion (sometimes referred to as 3D plotting). On the one hand, 3D powder printers allow complete design freedom and the additive production of volumes in free shapes; on the other hand the robot plotting allows greater flexibility in on-site positioning and transport. For recovery sites, ALM is best configured for the creation of high-engineered forms for the structural optimization capacity of components and the range of materials.

2014

Woven clay - Harvard GSD experiments in additive clay depositions: Jared Friedman, Heamin Kim and Olga Mesa, 2014 (Friedman et al., 2014);
3D printing regulation as construction technique, Fosters and Partners: Xavier De Kestelier, Enrico Dini, Giovanni Cesaretti, Valentina Colla, and Laurent Pambaguian, 2014 (Cesaretti et al., 2014);
FABbots - research in AM for architecture, IAAC Barcelona: Marta Malé-Alemany and Jordi Portell, 2014 (Malé Alemany and Portell, 2017).

2016

Robotic multi-dimensional printing based on structural performance, Tsinghua University Beijing and Tongji University Shanghai: Philip Yuan, Hao Meng, Lei Yu, and Liming Zhang, 2016 (Yuan et al., 2016);
Free form clay deposition in custom generated molds, University of NSW: Kate Dunn, Dylan Wozniak O'Connor, Marjo Niemela, and Gabriele Ulacco, 2016 (Dunn et al., 2016);
3D printed interlocking modules, Kent State University: Bian Peters, 2016 (Peters, 2016);
Materially informed design to robotic production: a robotic 3D printing system for informed material deposition, TU Delft: Sina Mostafavi and Henriette Bier, 2016 (Mostafavi and Bier, 2016);
3D printed pedestrian bridge,[46] IAAC Barcelona, Acciona, and Dshape: Areti Markopoulou, Alexander Dubor, Enrico Dini et.al., 2016.

2017

3D printing stay-in-place formwork for concrete slab, Mania Aghaei Meibodi, Mathias Bernard, Andrei Jipa, and Benjamin Dillenburger: ETH Zurich, 2017 (Meibodi et al., 2017).

2018

Towards Visual Feedback Loops for Robot-Controlled Additive Manufacturing, University of Sydney: Sheila Sutjipto, Daniel Tish, Gavin Paul, Teresa Vidal-Calleja, and Tim Schork, 2019 (Sutjipto et al., 2019);
Thermally Informed Robotic Topologies: Profile-3D-Printing for the Robotic Construction of Concrete Panels, Thermally Tuned Through High Resolution Surface Geometry, Carnegie Mellon University: Joshua Bard, Dana Cupkova, Newell Washburn, and Garth Zeglin, 2018 (Bard et al., 2019);
Spatial print trajectory - Controlling Material Behavior with Print Speed, Feed Rate, and Print Path Complex, Harvard GSD: Sulaiman AlOthman, Hyeonji Claire Im, Francisco Jung, and Martin Bechthold, 2019 (AlOthman et al., 2019);
Sparse Concrete Reinforcement in Meshworks, Royal Danish Academy of Fine Arts: Phil Ayres1, Wilson Ricardo Leal da Silva, Paul Nicholas, Thomas Juul Andersen, and Johannes Portielje Rauff Greisen, 2019 (Ayres et al., 2019);
Sub-Additive 3D Printing of Optimized Double Curved Concrete Lattice Structures, Cornell University: Christopher A. Battaglia, Martin Fields Miller, and Sasa Zivkovic, 2018 (Battaglia et al., 2019);
Large-Scale Additive Manufacturing of Ultra-High-Performance Concrete of Integrated Formwork for Truss-Shaped Pillars, XtreeE: Nadja Gaudilliere, Romain Duballet, Charles Bouyssou, Alban Mallet, Philippe Roux, Mahriz Zakeri, and Justin Dirrenberger, 2018 (Gaudilliere et al ., 2019).

Smart Assembly

This process refers to the use of robots for the installation or assembly of components. The most common end-effector for assembly processes is the gripper which is able to recognize a building material, grasp it, and place it in the target point in accordance with the design information. This design possibility has led many research centers to experiment with the construction of masonry walls in brick or stone. The use of the smart assembly on-site is optimal if the robot is able to recognize the surrounding environment and to optimize the movements to avoid collisions with objects or people.

2012

Brick Design, ETH Zurich: Tobias Bonwetsch, Ralph Bartschi, and Matthias Helmreich, 2012 (Bonwetsch et al., 2013).

46 3D printed bridge, IAAC: https://iaac.net/project/3d-printed-bridge/.

2016

Autonomous robotic assembly with variable material properties, Carnegie Mellon University School of Architecture: Michael Jeffers, 2016 (Jeffers, 2016);
The SPIDERobot: a cable robot system for on-site construction in architecture, University of Porto: Jose Pedro Sousa, Cristina Gasso Palop, Eduardo Moreira, Andry Pinto, Jose Lima, Paulo Costa, Pedro Costa, Germano Veiga, and Paulo Moreira, 2016 (Sousa et al., 2016);
Architectural geometry through robotic assembly and material sensing, Princeton University: Kaicong Wu and Axel Kilian (Wu and Kilian, 2016).

2018

Automatic Path Planning for Robotically Assembled Spatial Structures, ETH Zurich: Augusto Gandia, Stefana Parascho, Romana Rust, Gonzalo Casas, Fabio Gramazio, and Matthias Kohler, 2018 (Gandia et al., 2019).

Combined Processes

The combined or hybrid processes can result from the combination of subtractive, additive, or smart assemblies. Forming robots can also be included, that is the machines programmed to change the geometric configuration of the materials, most commonly metal sheets. The combined processes enhance the operational flexibility of the robots when used as multitasking elements. Combined processes also highlight the potential for communication between multiple hardware and robots, programmed in a dynamic system.

2012

Design Robotics - cutting and prototypical facade assembly, Harvard GSD: Martin Bechthold and Nathan King, 2012 (Bechthold and King, 2012);
Cloud of Venice installation, Taubman College University of Michigan: David Pigram, Iain Maxwell, Wes McGee, Ben Hagenhofer-Daniell, and Lauren Vasey, 2012 (Pigram et al., 2013);
Irregular substrate tiling, Greyshed: Ryan Luke Johns and Nicholas Foley, 2012 (Johns and Foley, 2013);
RDM vault, Hyperbody robotics workshop in Rotterdam, Wes McGee, Jelle Feringa, and Asbjorn Aondergaard, 2012 (McGee et al., 2013).

2014

An Investigation of Robotic Incremental Sheet Metal Forming as a Method for Prototyping Parametric Architectural Skins, Taubman College University of Michigan: Ammar Kalo and Michael Jake Newsum, 2014 (Kalo and Newsum, 2014).

2016

Robotics-based prefabrication in architecture, BAT Architecture: Xun Li, DongHan Shin, JinHo Park, and HyungUk Ahn, 2016 (Li et al., 2016);
Individual serialism through the use of robots in the production of large-scale building components, ERNE Switzerland: Martin Krammer, 2016 (Krammer, 2016).

2017

Robotic fabrication of stone assembly details, Taubman College, University of Michigan, Quarra Stone, and Matter Design: Ines Ariza, T. Shan Sutherland, James Durham, Caitlin Mueller, Wes McGee, and Brandon Clifford, 2017 (Ariza et al. , 2017).

2018

An Additive and Subtractive Process for Manufacturing with Natural Composites, Singapore University of Technology and Design: Stylianos Dritsas, Yadunund Vijay, Marina Dimopoulou, Naresh Sanadiya, and Javier G. Fernandez, 2019 (Dritsas et al., 2019);
Hard + Soft: Robotic Needle Felting for Nonwoven Textiles, Taubman College of Michigan University: Wes McGee, Tsz Yan Ng, and Asa Peller, 2019 (McGee et al., 2019);
Dynamic Robotic Slip-Form Casting and Eco-Friendly Building Façade Design, Tsinghua University: Lei Yu, Dan Luo, and Weiguo Xu, 2019 (Yu et al., 2019);
Dubai government office, construction by Winsun and design by Killa studio, Dubai, 2018.

In the state of the art at large, there are research projects aimed at developing tools for on-site construction. If robotic production in the industrial plant is now widespread, the TRL of on- site robotics is still confined to laboratory experimentation:

On-site Robotics

On-site robotic processes are performed by systems made "intelligent" by the implementation of sensors. These sensors represent a further evolution of the CAD / CAM relationship.[47] The sensors can be vision and tactile, with the function of extending the perception of the designer who acquires a new material or context sensitivity. The installation of sensors to extend the judgment and decision-making capacity of robots is useful to enrich the interaction between the robot and the complexities of the site environment. This application is under development although robotic sensors were already widespread in the 1990's but in applications where high capitalization costs were not overly prohibitive. Current on-site robotics technologies can include large-scale, small-scale, light-weight mobile mechanical arms for attention to detail, computerized platforms equipped with mechanical arms, autonomous driving vehicles, and soil moving vehicles.

2001

Contour crafting, CC Corp: additive construction technology invented and patented by Behrokh Khoshnevis from the University of Southern California[48] (Khoshnevis, 2004).It is a hybrid automated fabrication method that combines extrusion for forming the surface of an object and filling the process with purification or injection to the build of the object's core Khershnevis et al., 2001.

47 Construction robots - an overview: https://www.youtube.com/watch?v=nKGGHdl3NyQ&feature=youtu.be.
48 Contour crafting: http://contourcrafting.com/.

2012

Bemo Systems, collaboration with Ortic AB: Peter Mehrtens, 2012 Rapid on-site fabrication of custom free metal cladding panels (Mehrtens, 2013).

2014

A Mobile Large-Scale Platform for On-site Sensing, Design, and Digital Fabrication, MIT Cambridge: Steven Keating, Nathan A. Spielberg, John Klein and Neri Oxman, 2014 (Keating et al., 2014);
A Near Real-Time Approach to Construction Tolerances, Taubman College University of Michigan: Lauren Vasey, Iain Maxwell and Dave Pigram, 2014 (Vasey et al., 2014);
Design Approaches Through Augmented Materiality and Embodied Computation, Princeton University, Ryan Luke Johns, Axel Kilian and Nicholas Foley, 2014 (Johns et al., 2014);
Material Feedback in Robotic Production, Harvard GSD: Felix Raspall, Felix Amtsberg and Stefan Peters, 2014 (Raspall et al., 2014);
Kuka robots on-site, Kuka Robotics: Stuart Shepherd and Alois Buchstab, 2014 (Shepherd and Buchstab, 2014).

2016

Sensors and workflow evaluations: developing a framework for instant robotic toolpath revision, University of Sydney: Alexandre Dubor et. al., 2016 (Dubor et al., 2016);
Real-time adaptive fabrication-aware form University of Sydney: Dave Pigram, Iain Maxwell, and Wes McGee, 2016 (Pigram et al., 2016).

2017

Bespoke system operations for non-standard timber components, Architecture Association London: Martin Self, Emmanuel Vercruysse, 2017 (Self and Vercruysse, 2017).

2018

Haptic programming, Aachen University: Sven Stumm and Sigrid Brell-Cokcan, 2018 (Stumm and Brell-Çokcan, 2019);
On-Site Robotics for Sustainable Construction, IAAC Barcelona: Alexandre Dubor, Jean-Baptiste Izard2, Edouard Cabay1, Aldo Sollazzo, Areti Markopoulou, and Mariola Rodriguez, 2019 (Dubor et al., 2019).

2019

Hadrian X robot,[49] Fastbrick Robotics: Mark Pivac, ongoing development of the on-site construction technology since 1994.

49 In 1994, aeronautic and mechanical engineer Mark Pivac had the idea for a mobile dynamically stabilised robot. Between 2005 - 2008, Pivac filed patents for an 'automatic bricklaying system' and created the first Hadrian prototype. After successfully demonstrating the build of a wall using ground-mounted robots and mortar, production of Hadrian 105 was under way. After stalling during the 2008 financial crisis, development of the Hadrian 105 resumed in 2014 amid a stronger economy and renewed interest in robotic construction. In 2016, the Hadrian 105 built the world's first multi-room block structure from a 3D CAD model with no human intervention, providing proof of concept for what would become Hadrian X. In June 2018, the mechanical assembly of the first Hadrian X construction robot was completed.

Autonomous driving and soil moving technologies, CAT Caterpillar Inc., ongoing development of soil moving and autonomous driving construction tools for on-site operations;[50]
Construction robotics, ETH Zurich: Robotic systems Lab, the ongoing project targets novel technologies to enable robotified, architectural-scale and landscape-scale building processes;[51]
On-site robotics - Okibo, Kuka robotics: ongoing projects for on-site robotic applications.[52]

Drones

The remotely piloted aircraft systems are systems mainly used for digital surveying and reconstruction from photogrammetric information.

2014

Building with flying robots, ETH Zurich: Ammar Mirjan, Fabio Gramazio, and Matthias Kohler, 2014 (Mirjan et al., 2014);

2015

RPAS survey of the castle Delizia Estense del Verginese, University of Ferrara: Marcello Bolognesi et. al., 2015 (Bolognesi et al., 2015);

2016

Building a bridge with flying robots, ETH Zurich: Ammar Mirjan, Federico Augugliaro, Raffaello D'Andrea, Fabio Gramazio, and Matthias Kohler, 2016 (Mirjan et al., 2016).

To facilitate the reading of the case studies, it was decided to divide the examples into two macro categories:

- **disembodied craft;**
- **computer vision.**

Disembodied craft refers to technologies that perform tasks based on a given digital design input in a static, unidirectional manner. The designer's dexterity is embedded digitally to then be output with a temporal or geographic separation.[53] Disembodied craft is meant to be generic and regardless of the end-effector, toolpath, or kinematic features. Such systems are also called limited-sequence robotic systems or open loop systems (Keramas et al., 1998): the output signal is not dependent upon the output of the system. The term open loop is robot-centric because the robot is relying on instructions from a human.

50 CAT autonomous trucks: https://www.cat.com/en_MX/news/machine-press-releases/cat-autonomous-mining-trucks-haul-one-billion-tonnes.html.
51 Robotic systems lab - construction robotics: https://rsl.ethz.ch/research/researchtopics/dfab.html.
52 Kuka Okido: https://okibo.com/.
53 From Karl Daubman's lecture at the VI IDAUP workshop held in Ferrara. November 2019.

These systems are the simplest from an engineering perspective. Pick-and-place systems are an example where a set of operations is defined and simply repeated. An open loop system has no sensors on the robot arm to provide feedback. From the point of view of machine mechatronics, in the nineties these were called "non-intelligent robots". However, the technological transfer from the industrial to the architecture sector opens up a techno-optimistic approach, so the robot represents the extension of the designer's work space and at the same time the extension of the designer's arm. Within the process it is possible to discern where creativity might reside and in which phases it may not. Consequently, to decide depending on the case when the machine is configured as a simple executor, or when there is an exchange of architect-robot knowledge.

In contrast to the open loop systems described above, closed loop systems allow the robot to make decisions in real-time based on its previous output. Computer vision integrates robotic sensing systems that expand the cognitive abilities of the tool. The system allows for the collection of data and form an image that can be interpreted by a computer to to interpret an object. Through 2D and 3D scanners it is possible to collect data relating to the path of the robot during the production phases and carry out form recognition operations, so as to validate the data generated for process control. Programmable systems in feedback loops from an engineering point of view are called "higher intelligent robots".

These systems work according to a closed loop (Keramas et al., 1998): the output of the control is constantly compared to the output of the device. While uncommon from a systems engineering perspective, it can be speculated that a hybrid condition might exist where both open loop and closed loop systems might be most conducive to the range of constraints encountered on a restoration site. To better understand the relationship between manual operations and feedback loop operations, James Keramas illustrates a useful example in the publication *Robot Technology Fundamentals* (Keramas et al., 1998). A professional bricklayer usually uses one continuous movement to lay the mortar on a brick. There are numerous factors which regulate the trowel, such as the amount of mortar on the trowel and the consistency and weight of the mortar. Since mortar consistency changes rapidly, the bricklayer adjusts movements according to empirical training based on both visual and tactile inputs. The current advancement of technology makes it possible to program robots capable of learning from the human being by memorizing and reproducing the sequence of movements.[54] This process can be translated into lines of code in Grasshopper. This innovation is possible by installing a depth-sensing camera mounted on the end-effector. A surface approximation algorithm can be used to calculate the volume of the mortar, approximating each point as a volumetric box. The data is used to determine the ideal depth of the mortar, then back to the robot to adjust its depth. The limit switch connected to the digital input of the robot controller can be added to the end of the procedure. The

54 " MIT algorithm helps robots better predict human movement" in The Robot Report. Available at: https://www.therobotreport.com/mit-algorithm-helps-robots-better-predict-human-movement/. "Construction Robots Learn to Excavate by Mimicking Humans". Available at: https://spectrum.ieee.org/tech-talk/robotics/robotics-software/construction-robots-learn-to-excavate-by-mimicking-humans.

approach can then determine the variation between the computationally-derived brick and the actual position of the corresponding brick that results from the possible variations in the thickness of the mortar bed.

5.2.3 Analysis criteria

Case studies were analyzed with the logic of identifying potential and criticality within the processes that generated them. The reading of the analysis sheets starts with the technological classification in compliance with the UNI 8290 standards (articulation of the technological units) and UNI 7867 (definition of building and environmental systems). The reference categories (unit, subsystem, or architectural system) represent a cognitive approach that serves to deepen the problems inherent to the different phases of the building process. In particular, the progress of the design outcome is acknowledged, starting from the virtual model, to the proof of concept, to the research prototype, and the built project. Starting from the design decision-making phase, the case study analysis initially specifies whether a three-dimensional, parametric, algorithmic, or modeling design has been employed. Virtual simulations can be used to set up the fabrication-aware procedures that best communicate with the means of production. The factors that govern digital fabrication methods (additive, subtractive, smart assembly, and combined processes) are then defined, according to the different applications (exterior walls - roof - interior walls - interior floors - cladding - decoration) and in relation to the properties performative of the materials used (concrete - rammed soil - synthetic and combined materials).

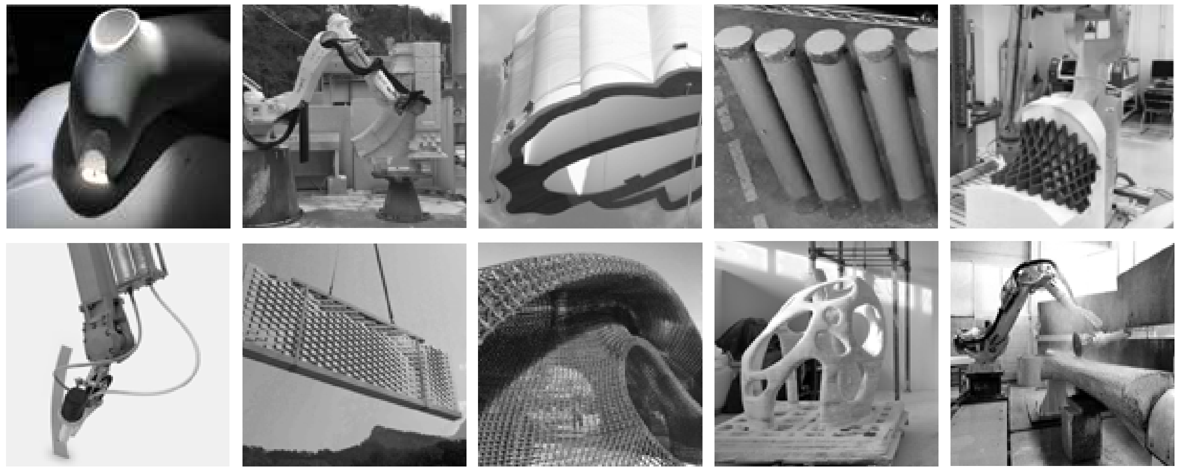
From the research point of technological innovation, the case studies are framed within a TRL, according to the H2020 specification, as an innovation of:

- process: that is the execution of non-linear iterative phases that deviate from the logics and flows of consolidated and traditional work;
- tool: the hardware development of sophisticated technological systems (visual and tactile sensing) and adaptable to the architecture sector and in particular for on-site operability;
- design: the inclusion of innovative design phases that exploit the potential of robotics to generate new formal opportunities.

The analysis is defined in such a way as to make the examples comparable and to draw up a critical reading regarding:

- the identification of potentialities and criticalities derived from the introduction of the proposed design methodology and of the new production methods in architectural practice and in industrial processes;
- the definition of the complexities deriving from the laboratory realization and the transposition of the processes to the on-site realization of full-scale architectural organisms;
- the elaboration of a priority scale for the complexities to be resolved that can be faced in order to reach the shared goal between industry and academy to innovate the construction process;
- the articulation of a laboratory hypothesis, evaluating the necessary tools, which gives answers to the complexity extrapolated from the processes and which is able to open a discussion on the theme of robotics and digital Heritage.

Disembodied craft



Winery ganterbain

Project data

University / research center: Gramazio Kohler Research at ETH Zurich
Project team: Gramazio Kohler Architects in cooperation with Bearth & Deplazes Architekten, Valentin Beath, Andrea Deplazes, Daniel Ladner. Industry partner: Keller AG Ziegeleien. Collaborators: Tobias Bonwetsch (project lead), Michael Knauss, Michael Lyrenmann, Silvan Oesterle, Daniel Abraha, Stephan Achermann, Christoph Junk, Andri Lüscher, Martin Tann, Jürg Buchli, Dr. Nebosja Mojsilovic and Markus Baumann
Equipment: 7-axix Kuka robots, grippers end-effector and gluing system
Digital tools: parametric design, algorithmic scripting, and robo-programming
Year: 2006

Scale:

- technological unit
- **technological subsystem**
- architectural system

Project applications:

- **exterior walls**
- roof
- interior walls
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- **mono-material**
- multi-material

- **low-engineered**
- high engineered

- **ceramic**
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- **3D modelling**
- **parametric design**
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- **smart assembly**
- combined processes

TRL target:

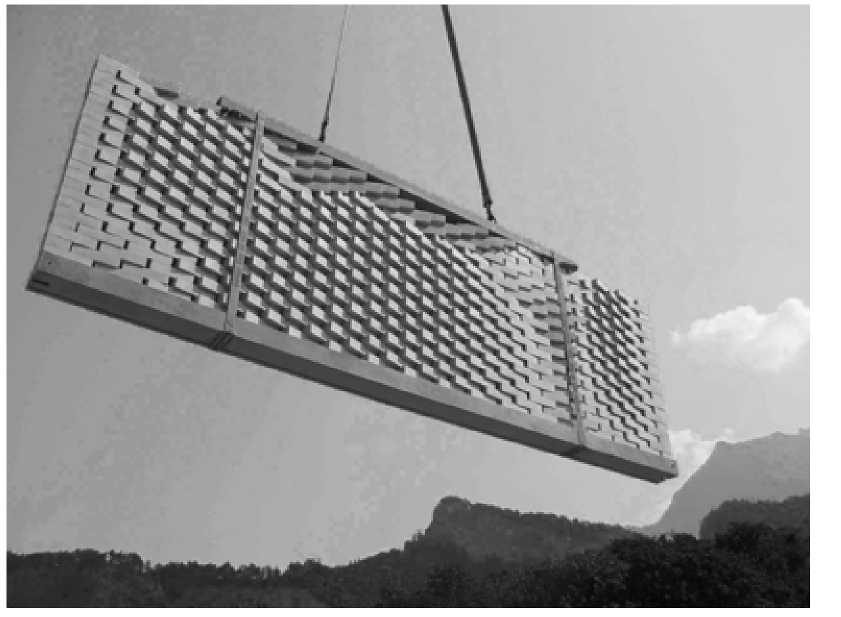
- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- **development (4-5-6)**
  - experimental pilot
  - **demonstration pilot**
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- lack of a predictive model
- **workcell management**
- load bearing properties
- **on-site installation**
- **on-site assembly**
- **resource consumption**
- **scalability**
- interface of the elements produced with complex surfaces
- level of detail of the outcome
- development of new materials



Description

The project is the extension of a winery in Fläsch, Switzerland. The aim was to build a fermentation room for processing grapes. The Gramazio and Kohler studio was responsible for the construction of the building's façade. The design language is that of the staggered brick surface creating an articulated geometric effect. This approach also has a functional purpose, i.e. to filter the direct light that would negatively affect the wine production processes. Polycarbonate panels are mounted inside to protect the envelope from the wind. The bricks form the balustrade of the terrace, on the upper floor. The construction of the facade took place off site, in the laboratory, and organized in rectangular modules. The process was carried out through robotic production developed at ETH. A 7-axis robot was implemented with a gripper which served to lay 20,000 bricks following programmed parameters, with variable angles on the horizontal plane and within certain intervals. Depending on the installation angle, the individual bricks reflect the light differently, thus assuming different degrees of lightness, plasticity and depth of color.

Feedback

The wall elements were produced as a pilot project at the research facilities at ETH Zurich, transported by truck to the construction site and installed with a crane. The use of robotics made it possible to create 72 facade elements of the building in less than three months, with very high architectural and compositional quality. Since the robot could be guided directly by the design data, without having to produce further implementation drawings, the researchers were able to work on the façade design until the last minute before production began. This is one of the most relevant aspects when it comes to parametric design and algorithmic programming. Extending the design time allows the quality of the result to be increased and the errors that can be made during the construction phase to be minimized. To speed up the production process of the 400 square meter façade, the design team has designed an automated process for the application of the two-component binder. As each brick has a different rotation, each individual brick has a different and unique overlap with the brick below and the brick above. The solution was to establish a method in which the following are applied four parallel paths of the binding agent, for each individual brick, at predefined intervals on the central axis of the wall element. Load tests carried out on the first elements produced revealed that the bonding agent was so structurally effective that reinforcements normally required for conventional prefabricated walls were not necessary. The project dates back to 2006 and has paved the way for international research large scale robotic digital fabrication.

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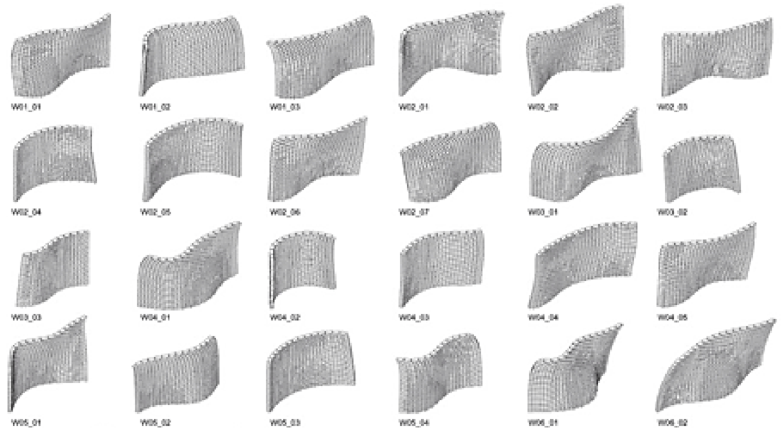
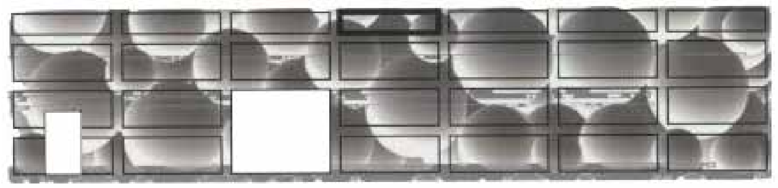
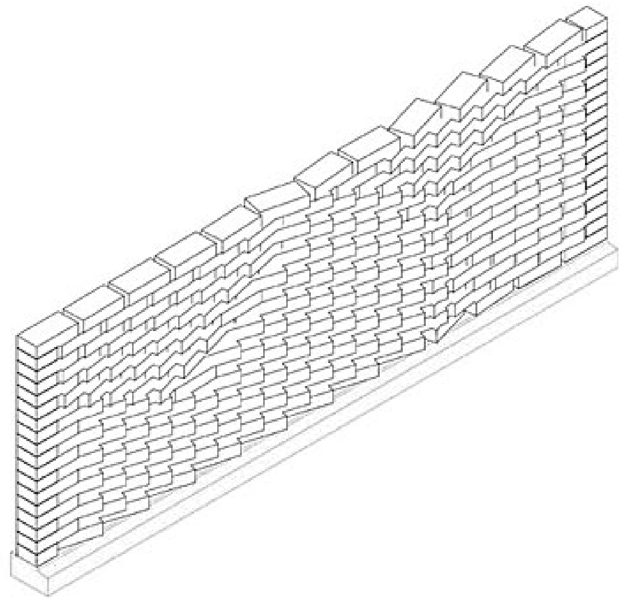






Radiolaria pavilion

Project data

University / research center: Norman Foster Research Foundation
Project team: Andrea Morgante (Shiro Studio), and Enrico Dini (Dshape)
Research program: Rapid Prototyping and Rapid Manufacturing at Foster + Partners
Equipment: Dshape 3D printer
Digital tools: parametric design
Year: 2008

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- cladding
- decoration
- **scale model**

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- **composite materials**
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- **parametric design**
- algorithmic scripting
- **virtual simulation**

Fabrication process:

- **additive**
- subtractive
- smart assembly
- combined processes

TRL target:

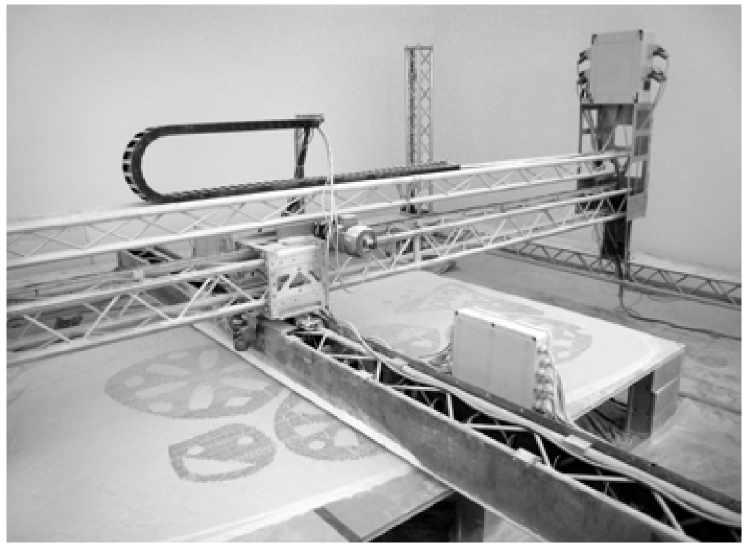
- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- **development (4-5-6)**
  - **experimental pilot**
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- lack of a predictive model
- **workcell management**
- **load bearing properties**
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials



Description

Radiolaria's goal was to produce geometry that could be self-supporting and demonstrate the capabilities of emerging large-scale 3D printing. The technology is based on powder deposition of sand and mineral powder combined with inorganic binders and allows complex shapes to be constructed without the use of temporary formwork or disposable moulds. The binder transforms the mineral powder into a stone-like material with microcrystalline characteristics and tensile strength superior to Portland cement, as demonstrated by the results of tensile, compression, and flexural tests. Magnesium carbonate was used as the main aggregate. The design of the pavilion has been realized without any internal steel reinforcement. The stamante used is Cartesian type, with external reticular structure to support the heads that deposit overlapping layers of material. The process starts from the design file, which is converted into STL format and imported into the software that controls the printer. The printing of each section takes place in a continuous work session. During printing, the binder, called structural ink, is deposited by the printer's nozzles on the sand. The solidification process takes 24 hours. Printing starts at the bottom of the construction and rises in sections of 5-10 mm each. On contact, the solidification process begins and a new layer is added. The excess sand that has not been incorporated into the structure acts as a support while the solidification process takes place. This excess sand can then be reused on future prints.

Feedback

Radiolaria was the first ever example of large scale additive layer manufacturing. Nothing like this had ever been done before. The development of the project put pressure on the scientific research sector. The result was to demonstrate not only the symbiosis between language and process, but also the independence of the process itself from post-process or post-production actions. Radiolaria wanted to demonstrate the possibility of generating a fluid and innovative workflow between formal generation and project completion. The sending of the 3D data file to the press and the printing of a fully structural full-scale project, without other intermediate actions, made the designer aware of the full potential of this process and how much more can be achieved in this direction.

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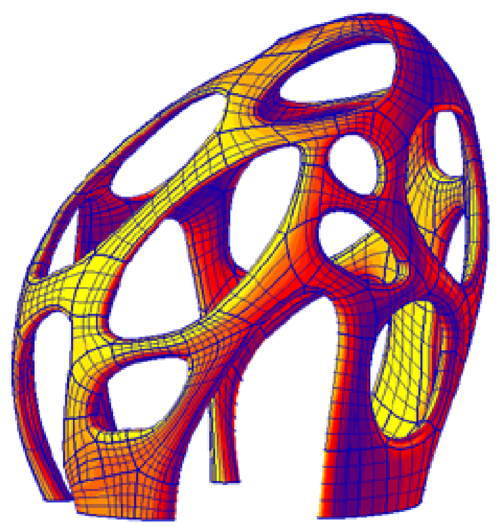
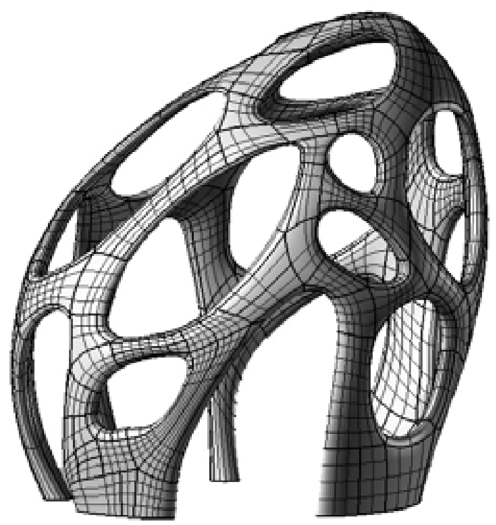
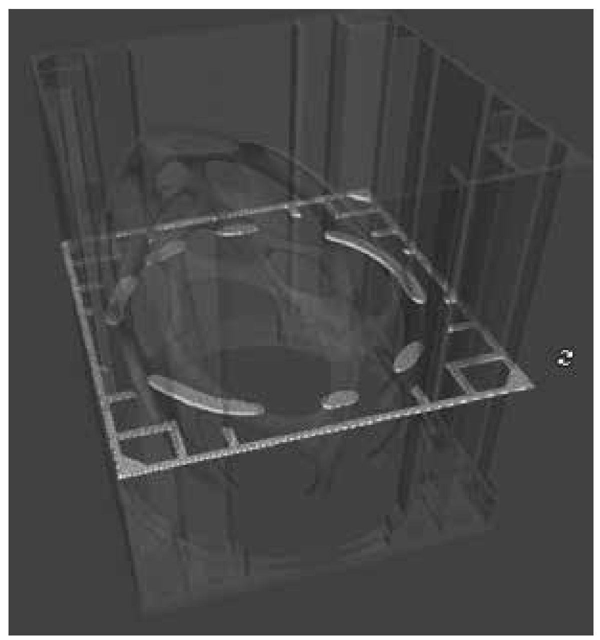






Periscope

Project data

University / research center: University of Michigan TCAUP FABLab
Project team: M Brandon Clifford and Wes McGee in collaboration with Matthew Johnson, Simpson Gumpertz & Heger, and Dave Pigram - Supermanoeuvre. Build team: Maciej Kaczynski, Johanna Lobdell, Deniz McGee, and Kris Walters
Research program: Modern Atlanta 10up! Competition
Equipment: Robot Kuka 7-axis
Digital tools: algorithmic programming and robo-scripting with custom Grasshopper plug-in
Year: 2010

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- **exterior walls**
- roof
- interior walls
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster
- **foam**

Design process:

- 3D modelling
- parametric design
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- **subtractive**
- smart assembly
- combined processes

TRL target:

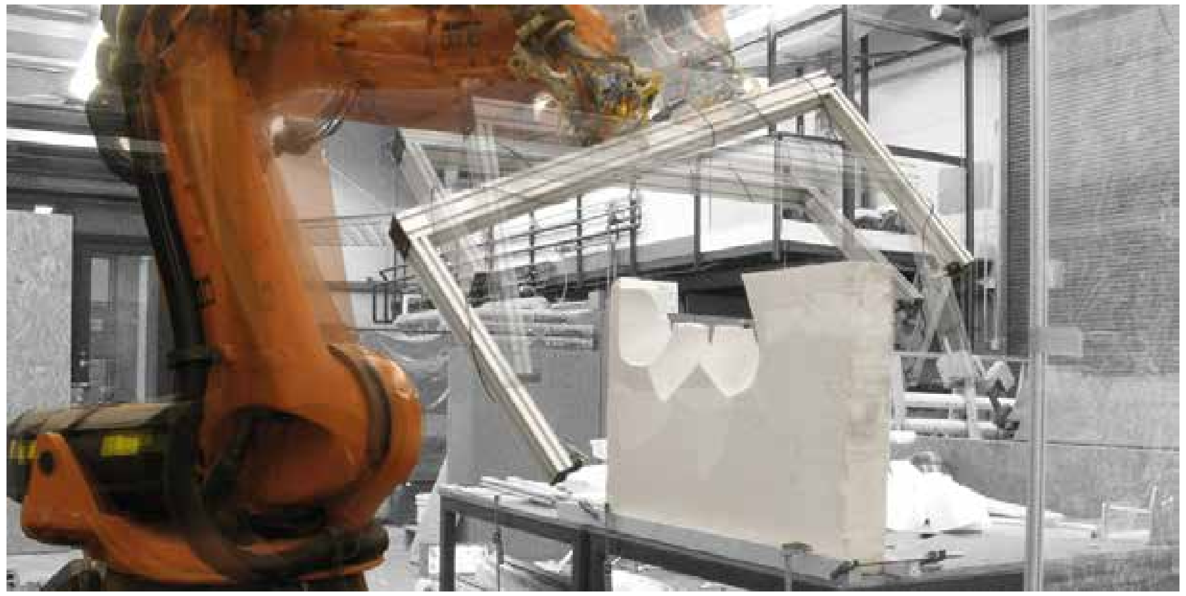
- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- **development (4-5-6)**
  - experimental pilot
  - **demonstration pilot**
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- uncertainty management
- lack of a predictive model
- **workcell management**
- load bearing properties
- on-site installation
- **on-site assembly**
- resource consumption
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials



Description

Brandon Clifford and Wes Mcgee of Matter Design Studio have won a competition at the Young Architects competition in Atlanta. Participants submitted a proposal for a temporary installation. The project, called Periscope, is a 13-meter tower made of expanded polystyrene that has been processed through robotic hot wire cutting. Assembled in only 6 hours, the inclined tower stands on an internal wooden frame, which was assembled and stabilized using tensioning steel cables fixed to the base, a wooden box hiding counterweight blocks. The tower was built in sections to make it possible to hot wire cut doubly curved surfaces. The sections in turn have been divided into quarters, compatible with the robotic workcell, i.e. the reachability range of the axes in space. The architects used a 7-axis robot, capable of moving linearly on a track anchored to the ground. The design was done using custom plug ins for Grasshopper, developed in the laboratories of the Taubman College of Architecture and Urban Planning to make the design/programming more accurate than software defined by standard features.

Feedback

The project challenges the traditional approach to architectural construction. The hot wire cutting robotic was used to generate a wide range of mass customized units, which make up a volume defined by double curvature surfaces. The material used is synthetic and lightweight and has been pushed to assume the role of a technological building component. The large dimensions of the single discrete pieces open the possibility to explore new assembly systems not necessarily related to human proportions, such as brick, for construction and installation. In addition, through this tower is highlighted the attempt to scale-up the processes of robotic digital fabrication. It has also demonstrated the process efficiency and the high quality of the formal/compositional result, without any significant increase in construction costs. In this case it was decided to program the construction of the components offsite, and then transport the parts to be assembled to the construction site. However, the project dates back 10 years and in the meantime the robotic research sector is confident enough to say that the workflow can be easily transferred on-site with the use of robots or mobile platforms directly to the project site.

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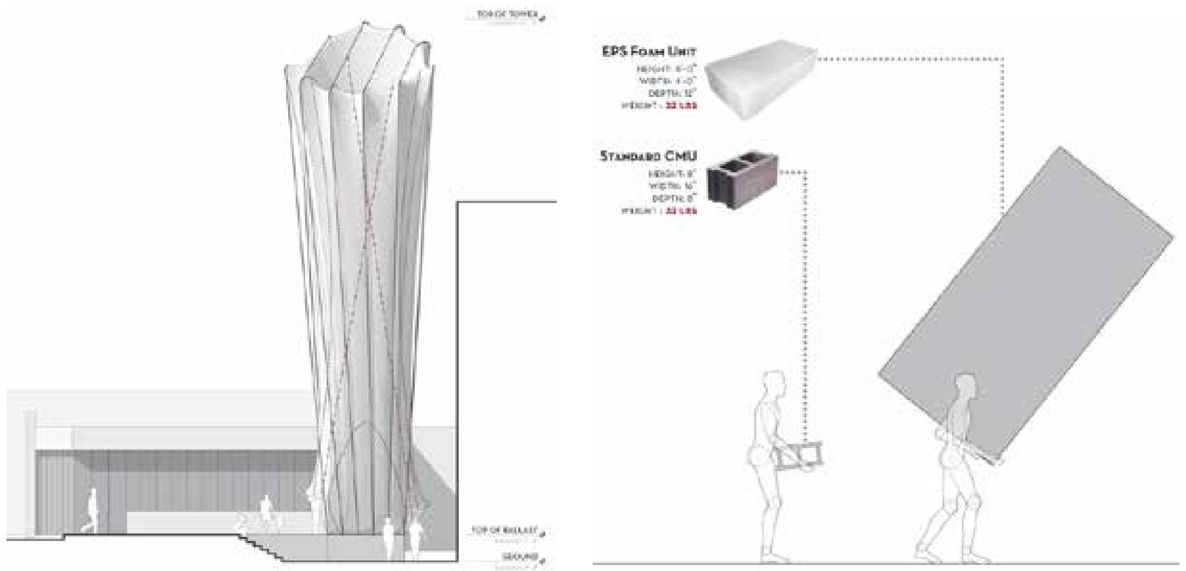


Mataerial

Project data

University / research center: Institute for Advanced Architecture of Catalonia (IAAC) in collaboration with Laarman Studio
Project team: Petr Novikov, Saša Jokić, Joris Laarman, Tim Geurtjens, Fabian Scheurer, Luis Fraguada, Gijs van der Velden, Stefanie Riegman, Mette Thomsen, and Areti Markopoulou
Research program: IAAC Open Thesis Fabrication Program
Equipment: 6-axis abb robots, plastic polymer extruder end effector with cooling system, and thermosetting polymers
Digital tools: algorithmic design and roob-scripting
Year: 2013

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- cladding
- decoration
- **scale model**

Outcome advancement:

- virtual model
- **proof of concept**
- research prototype
- built project

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- composite materials
- **plastic**
- concrete
- plaster

Design process:

- 3D modelling
- parametric design
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- **additive**
- subtractive
- smart assembly
- combined processes

TRL target:

- **process innovation**
- **tool (machine or end-effector)**
  - visual sensing
  - tactile sensing
- design outcome

TRL advancement:

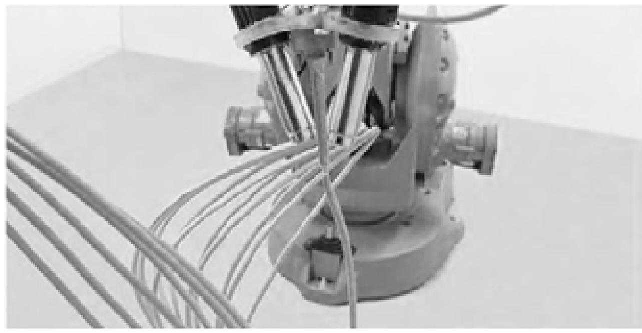
- **research (1-2-3)**
  - basic principles
  - **concept and application formulation**
  - concept validation

- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot

- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- uncertainty management
- **lack of a predictive model**
- workcell management
- **load bearing properties**
- on-site installation
- on-site assembly
- **resource consumption**
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- **development of new materials**



Description

Mataerial is an additive robotic production methodology. It allows to create extrusions in three-dimensional space without the need for additional support structures. Conventional additive manufacturing methods, in particular desk-3D printing, are influenced by both gravity and the printing environment. Mataerial tries to break out of these technical constraints to explore the topic of additive manufacturing on irregular or non-horizontal surfaces. For this purpose, researchers have developed a material sufficiently resistant to be anti-gravity. Through the system of extrusion, and instantaneous cooling, the laboratory experiment has led to the definition of abstract shapes in space able to neutralize the effect of gravity during the printing process. This method offers the flexibility to create truly natural objects by creating 3D curves instead of 2D layers. Unlike 2D layers that do not know the structure of the object, 3D curves can follow the exact stress lines of a custom shape.

Feedback

One of the key innovations in anti-gravity object modeling is the use of thermosetting polymers, instead of thermoplastics commenly used in 3D printers. The material is polymerized through a chemical reaction between two components with a certain proportion of extrusion speed and kinematics such that the material exits the nozzle in the solid state. This feature makes it possible to print suspended curves without substrate material. The Mataerial project was conducted using experimental materials that were not compatible with the architectural construction. Despite this, there are many aspects that are considered relevant from the point of view of the advancement of additive manufacturing research under complex geometric conditions. The possibility of extruding self-supporting layers within a certain degree of scalability, opens up future speculation on the use of this system for temporary interventions or in support of the installation phases of technological components.

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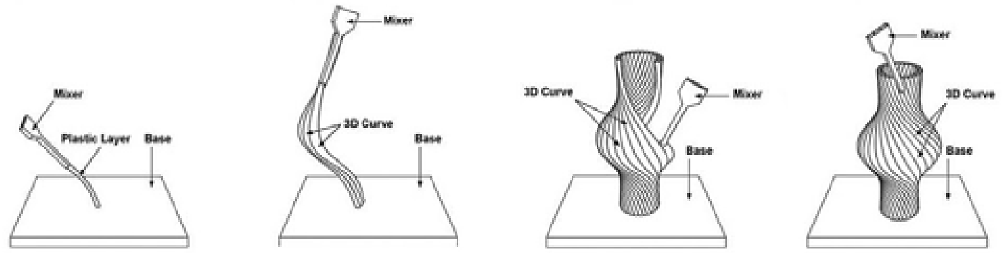
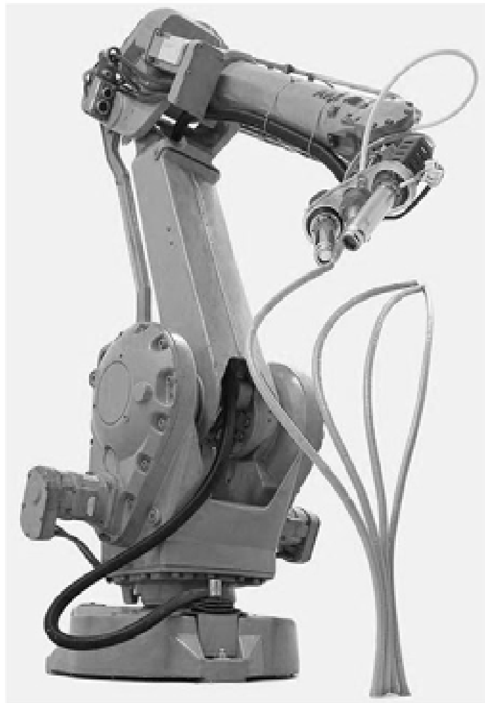
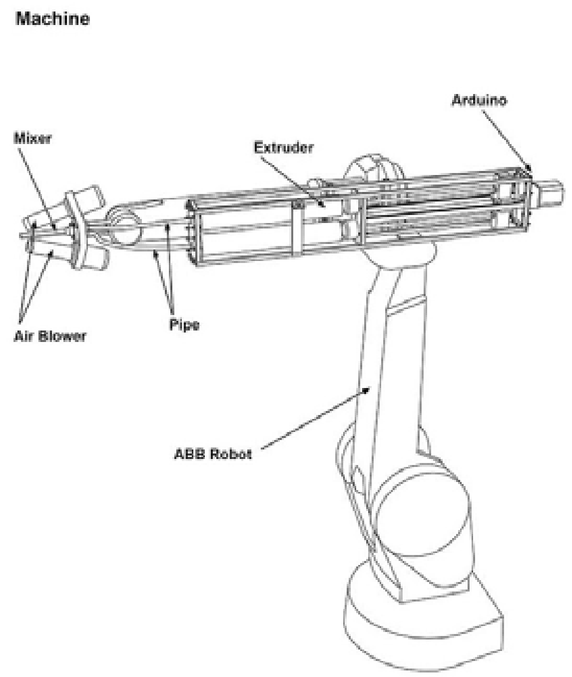






Robopinch, push, pull

Project data

University / research center: Taubman College of Architecture and Urban Planning, University of Michigan, Ann Arbor, USA
Project team: Karl Daubmann, Ric Foley, and Stella Zhang
Research program: Research through Making
Equipment: Kuka KR Agilus with Teach Pendant
Digital tools: teach pendant
Year: 2014

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- cladding
- decoration
- **scale model**

Outcome advancement:

- virtual model
- **proof of concept**
- research prototype
- built project

Materials:

- **mono-material**
- multi-material

- **low-engineered**
- high engineered

- ceramic
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- **plaster**

Design process:

- 3D modelling
- parametric design
- algorithmic scripting
- virtual simulation
- **teach pendant**

Fabrication process:

- additive
- subtractive
- smart assembly
- **combined processes**

TRL target:

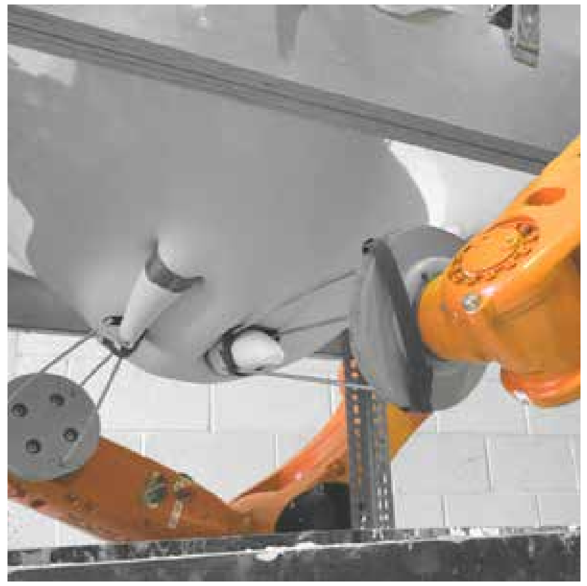
- process innovation
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

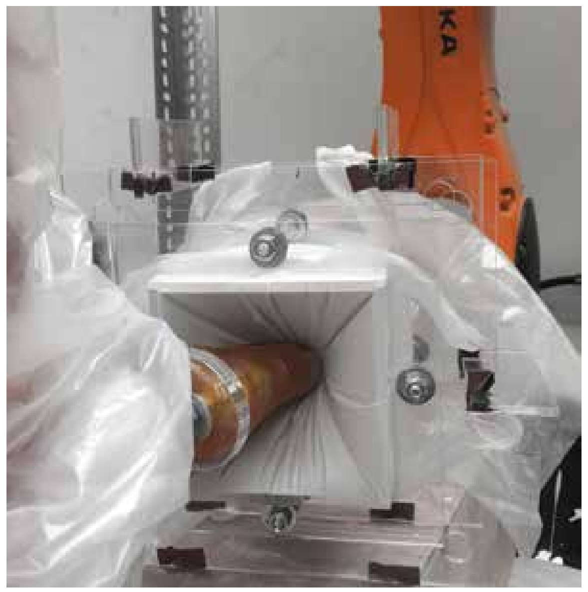
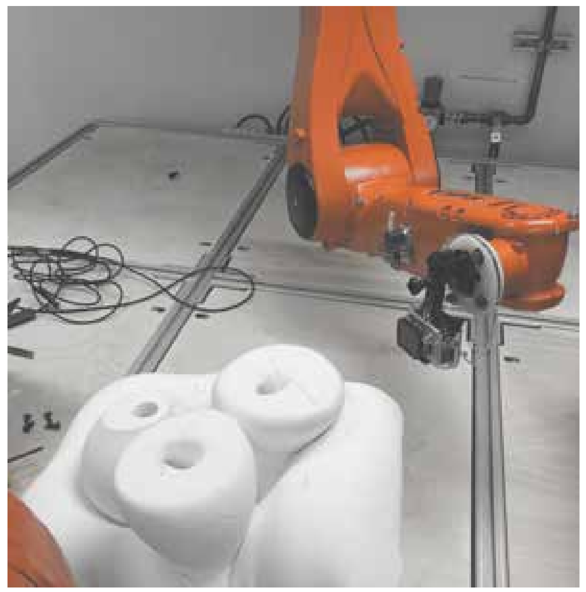
- **research (1-2-3)**
  - basic principles
  - **concept and application formulation**
  - concept validation
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- **uncertainty management**
- **lack of a predictive model**
- workcell management
- load bearing properties
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- **interface of the elements produced with complex surfaces**
- level of detail of the outcome
- development of new materials





Description

RoboPinch is an experiment carried out using two table robots to generate architectural models using plaster. Using plaster as the sun medium provides a versatile material that is quickly, inexpensive, and light wight. The goal was to generate volumes in complex forms through the scripting of only the kinematic paths of robots. No 3D model existed, only a set of robot instructions. The process sets out to explore the processing of a low-engineered material not directly with the hands but using a high precision automated intermediary. As the investigator stated, unlike the a priori file-to-factory design approach, this speculative exercise "allows the material to have a voice". A range of flexible surfaces was used as the formwork. The fabricated type and surface texture were tested and deployed based on the size of the cast or the robotic interaction. The reproducibility of robotic actions and static jigging meant that additional studies could be carried out. This way of making reinforced the parametric mentality that envisioned families of forms as opposed to only one idealized output. The RoboPinch work is broken down into initial studies and final models that build on knowledge gained through the initial studies. These studies are quick and iterative. Final models then bring multiple cast parts together on a plaster base as a means of studying architectural ideas about a building massing and its relationship to a landscape or topography.

Feedback

RoboPinch differs from the numerous experiments in the field of robotic digital fabrication which focus on emphasizing the precision of the machine in terms of accurate translation of design from the immaterial to the physical space. CAD-CAM relationship is often explored so that the intelligence of the project resides only in the digital model, while robots and 3D printers are mere executors. The RoboPinch outcomes are instead an exploration on materiality, discovering and advancing the form beyond that of the existing digital model, to establish a new material sensitivity between man and machine. The interaction of the material through a robot allows to maintain an artisanal approach in manufacturing procedures. It minimizes the uncertainty of the result and at the same time il leaves exploratory possibilities open. The use of a robot as a mechanical extension of the hand has allowed the achievement of complex morphologies without limiting the creativity of the designers and exploring the expressive potential of the plaster.

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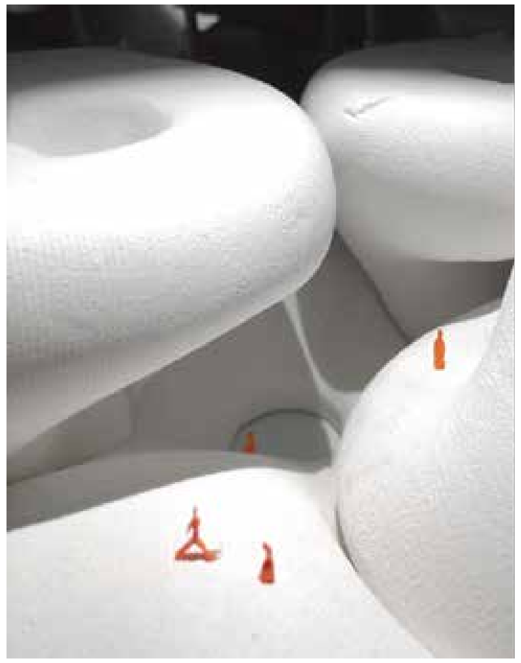

Arch of Palmyra

Project data

University / research center: Institute of Digital Archaeology, Oxford University, Dshape, and Torart.
Project team: team leaders Roger Michel, Alexy Karenowska, Enrico Dini, Giacomo Massari, and Filippo Tincolini.
Research program: World Heritage Week
Equipment: 6-axis ABB milling robot
Digital tools:
Year: 2016

Scale:

- technological unit
- **technological subsystem**
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- cladding
- **decoration**
- **scale model**

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- **stone**
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- **3D modelling**
- parametric design
- algorithmic scripting
- virtual simulation

Fabrication process:

- additive
- **subtractive**
- smart assembly
- combined processes

TRL target:

- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- design outcome

TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- **development (4-5-6)**
  - **experimental pilot**
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- uncertainty management
- **lack of a predictive model**
- **workcell management**
- load bearing properties
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials

Description

In 2015, the Institute of Digital Archaeology sponsored the elaboration of a mapping of archaeological sites and culturally relevant artefacts for the creation of an archive of digital three-dimensional data giving priority to areas subject to political and cultural calamities. Among the works classified as Heritage protected by UNESCO, the IDA examined the archaeological site of Palmyra. The images collected were assembled using a photogrammetric technique. This experimental activity led to the exhibition in London, in the context of the UNESCO World Heritage Week 2016 event, of a scale reproduction of the Palmyra triumphal arch. The prototype was made using the numerically controlled milling technique96 on the basis of the digital data obtained from the photogrammetric survey. A six-axis robotic arm was programmed to perform subtractive processing on Egyptian marble blocks, selected for their color characteristics (similar to those of the technological units that make up the monuments of Palmyra) and for the material processing properties of the stone. Several discrete elements were then assembled to make up the reproduction of the arc.

Feedback

The arch represented a test-bed for the use of digital fabrication for Heritage and for the dissemination of knowledge on global Cultural Heritage. It represented one of the first examples of dissemination of the technological capabilities acquired by the scientific community in the field of Architectural Heritage conservation. The experiment can be analyzed according to the following objectives achieved: 1) collection of the photographic documentation of the site based on pre-destruction information, due to the lack of a preventive digital survey and the temporary inaccessibility of the area; 2) definition of a digital three-dimensional model that can be used to systematize restoration interventions in a post-emergency context; 3) tests for the implementation of construction units that can be assembled on the architectural scale using automated tools; 4) realization of a scaled-down prototype to verify times, costs, precision, of the robotic instrument in realizing an architectural portion consisting of a decorative apparatus. A further key point that can be considered as a goal achieved was to encourage, in the following years, the scientific community to open a dialogue between restoration and digital manufacturing.

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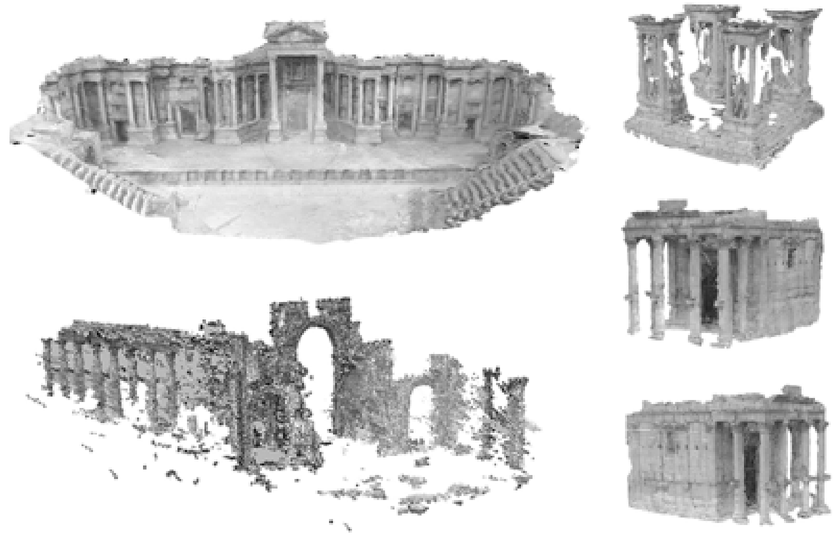


Informed ceramics

Project data

University / research center: B.A.T. Seoul, Korea
Project team: Minjae Ko, Donghan Shin, Hyunguk Ahn, and Hyungwoo Park
Research program: B.A.T. research in robotics
Equipment: multi-axis clay 3D printing on by installing a hot wire cutter, a spindle, and a clay extruder on a desk-robot head
Digital tools: in-house Gerty and Robot Studio plug-ins using Grasshopper
Year: 2018

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- **cladding**
- **decoration**
- scale model

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- **low-engineered**
- high engineered

- **ceramic**
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- parametric design
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- **additive**
- subtractive
- smart assembly
- **combined processes**

TRL target:

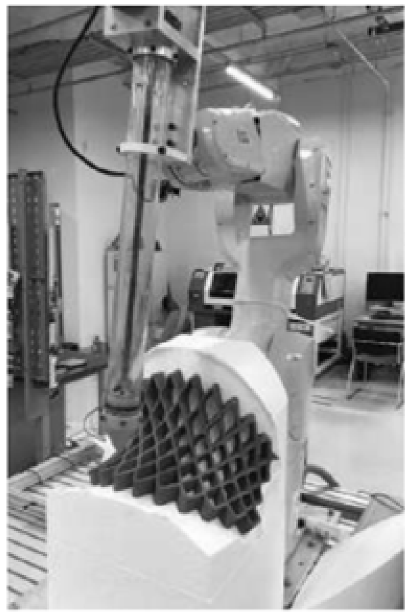
- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- **design outcome**

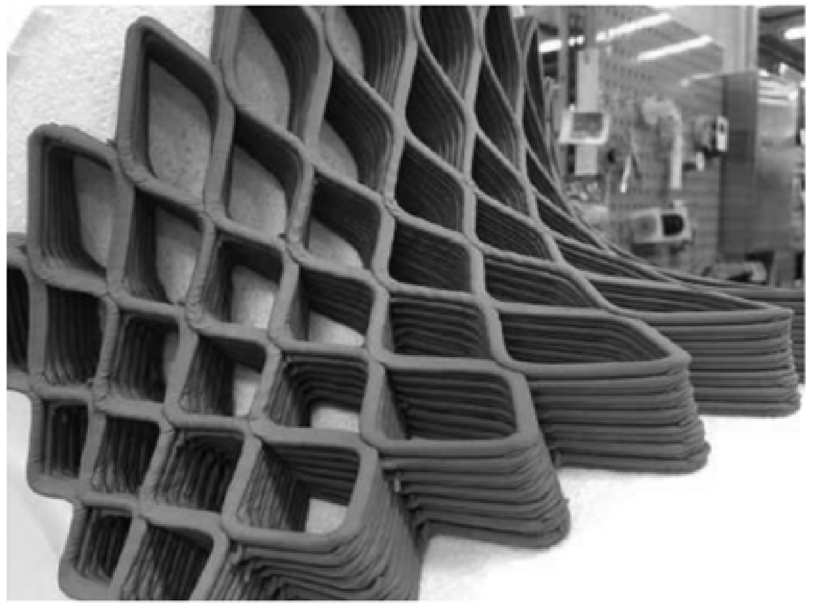
TRL advancement:

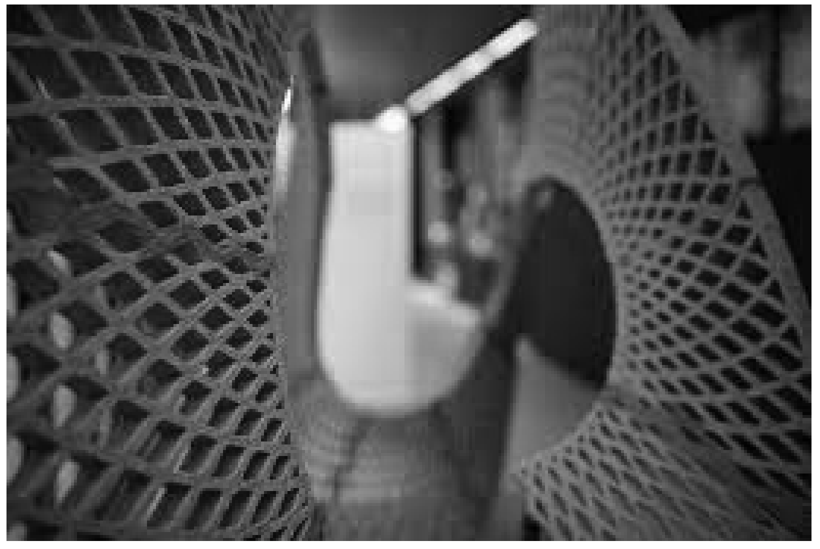
- **research (1-2-3)**
  - basic principles
  - concept and application formulation
  - **concept validation**
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- **digital process management / modeling**
- production process management
- **uncertainty management**
- lack of a predictive model
- workcell management
- **load bearing properties**
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- **interface of the elements produced with complex surfaces**
- level of detail of the outcome
- development of new materials







Description

In 2018 the University of Seoul refined the technical procedure of robotic extrusion of ceramic material on a doubly inclined curved surface. To achieve an optimal result, the researchers made several iterations for the definition of the end effector, especially given the need to store enough material to reduce refill operations. The robot deposited porous clay on a freeform mold using the developed syringe-type clay extruder. The processed panel was designed with a diagrid pattern to secure structural stiffness after drying and kiln firing. Before making the final mold, 3D printing tests were carried out to understand the maximum inclination on which to perform extrusion operations based on the number of overlapping layers, before the material collapsed. The toolpath was designed to make the extruded clay bodies overlap and conjoin at nodal points. In-house Gerty and Robot Studio plug-ins using Grasshopper were used to conduct accurate simulation of the robot behavior and create the toolpath. Using the syringe clay extruder, the researchers deposited clay on free-form molds. The 3D printed panel was designed with a grid model to ensure structural rigidity after drying and baking. The toolpath consists of a single continuous curve and is designed so that the extruded clay bodies overlap and join at nodal points. The researchers also applied the methodology proposed for the construction of a larger ceramic structure, composed of panels customized by parametric architectural language.

Feedback

Through the Informed Ceramics project, researchers have verified the feasibility of producing ceramic building components through robotic digital fabrication. The implementation of that technique will help to meet the needs of the construction industry of the future. It will be possible to imagine the possibility of creating customized modular constructions at low cost and high architectural quality. This project has successfully demonstrated the large-scale application of a new 3D robotic clay printing process. At the same time, several oeprative limitations were highlighted. Firstly, the extruder used also acts as a clay container, which becomes an element of complexity. In fact, in the manufacturing process, the overall efficiency of the work has decreased because the work had to be stopped several times to replace the polycarbonate tube of the extruder to be filled with new clay. Secondly, there was deformation of the product in the drying and firing process after the clay panel was formed. The contraction speed difference between the printing product and the mould and the high temperature inside the kiln produced a thin deformation of each panel. Future lines of research are aimed at improving the material and its processing to avoid deformations that cannot be controlled. The material container can also be moved away from the nozzle so that the additive production process does not have to be interrupted every time the volume of clay is consumed. Finally, an important development for the construction sector is the combination of research and materials science for the development of structurally high performance engineered materials.

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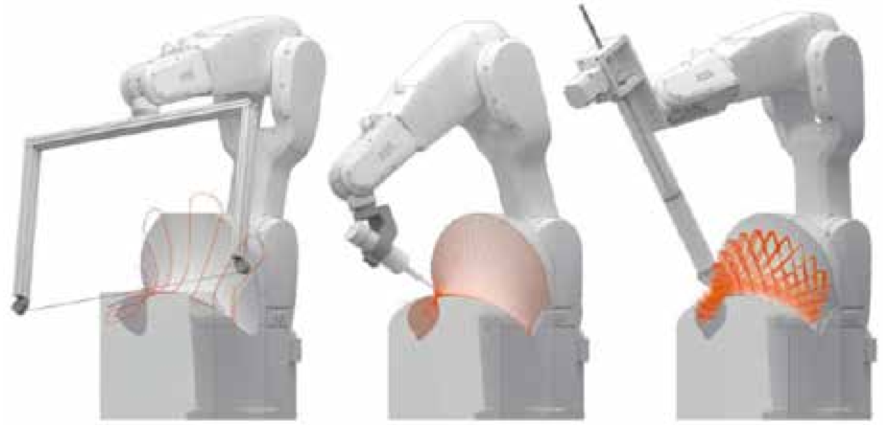
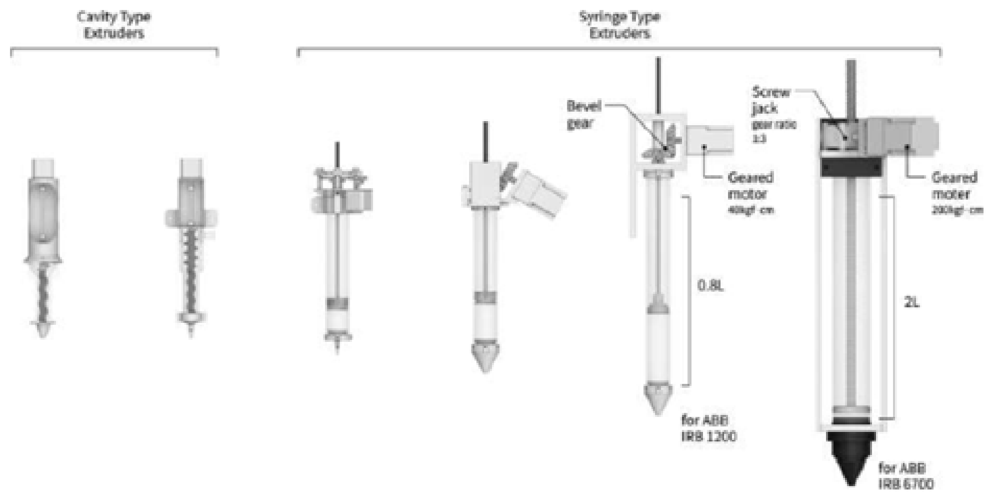




One city pavilion

Project data

University / research center: Branch Technology
Project team: Melody Rees and Jason Vereschak from Branch Technology, in collaboration with Thornton Tomasetti Core, and Range Projects
Research program: Branch Technology C-Fab™
Equipment: 6/7 axis robot, extruder installed on the robot head, and nozzle
Digital tools: parametric design, robo-programming
Year: 2018

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- **exterior walls**
- roof
- interior walls
- interior floors
- **cladding**
- **decoration**
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- **composite materials**
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- **parametric design**
- **algorithmic scripting**
- virtual simulation

Fabrication process:

- **additive**
- subtractive
- smart assembly
- combined processes

TRL target:

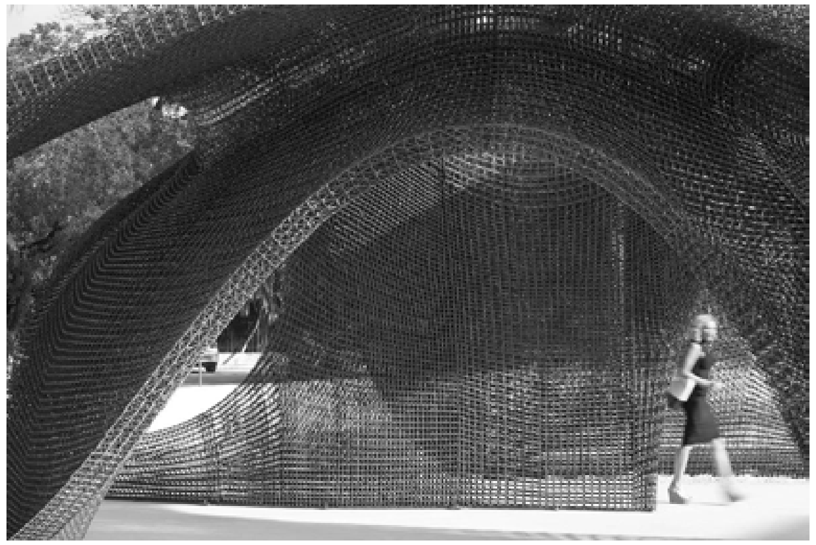
- **process innovation**
- **tool (machine or end-effector)**
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- **deployment (7-8-9)**
  - early stage implementation
  - **release version**
  - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- uncertainty management
- lack of a predictive model
- workcell management
- **load bearing properties**
- **on-site installation**
- on-site assembly
- **resource consumption**
- **scalability**
- interface of the elements produced with complex surfaces
- level of detail of the outcome
- **development of new materials**



Description

Branch Technology has patented a 3D printing process called Cellular Fabrication, C-Fab™. It allows the material to solidify in open space, creating a polymer matrix that can adapt to any shape with good structural strength. The extruded elements are fused together or connected to each other to form a cellular structure. The polymeric insulating foam can be used as a filler within the cell structure to contribute to strength and stiffness. The One City Pavilion was created by the commission of the developer Cambridge Inc. The client's formal proposal in an initial phase of analysis revealed that the volume of the pavilion would require an expensive steel sub-structure to support the loads. To optimize the design of the structure and to eliminate the need for additional steel reinforcement, the Branch Technology team designed a lightweight open cell structure using the C-Fab™ system. The team printed in 3D using robotic digital fabricaiton 40 panels offsite, then installed on the project site. The result is a space envelope free of conventional structural systems and pure in terms of geometric strength. Where the thrust and compression forces are greater, the material thickens. Where the lifting forces are high, the voids are carefully sculpted.

Feedback

The pavilion is the result of multidisciplinary work combining engineering, building production and construction. Branch Technology's main challenge is to scale robotic 3D printing to architectural dimensions. The entire pavilion is divided into 36 parts that extend up to half a meter and have an average weight of 80 kg. After off-site production, the completion parts were shipped to the construction site. To facilitate assembly, the various components fit together like a 3D puzzle. This technological approach can be successful in the near future in the construction industry because it is highly adaptable and flexible. One City Pavilion demonstrates how the scalability of projects does not affect the architectural quality of the result. Being able to work in an additive way with the extrusion of geometries in free shapes can be useful for structural consolidations or for post-emergency building safety actions. For new constructions, the frontier to be demolished is the use of natural materials and at the same time structurally performing. In this way it will be possible to see applications in construction at all technological scales.

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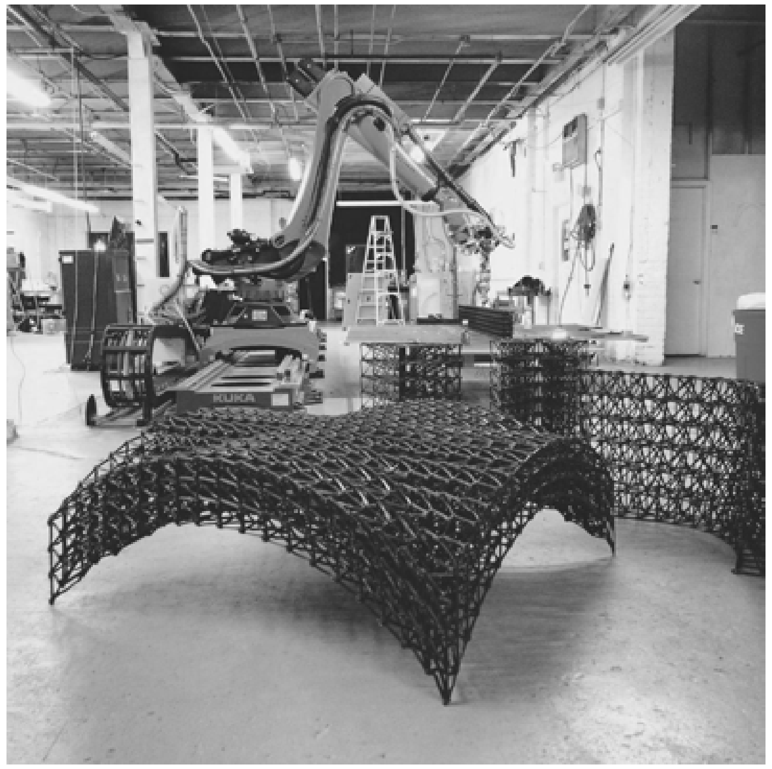

Ceramic vessels

Project data

University / research center: Taubman College of Architecture and Urban Planning, University of Michigan, Ann Arbor
Project team: Mark Meier and undergrad/grad students at UofM
Research program: ARCH 409 - Digital Fabrication class
Equipment: Kuka agilus / KR210
Digital tools: Rhinoceros + Grasshopper (programming), Kuka|Prc (scripting)
Year: ongoing

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- cladding
- decoration
- **scale model**

Outcome advancement:

- virtual model
- **proof of concept**
- research prototype
- built project

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- **ceramic**
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- **3D modelling**
- parametric design
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- **additive**
- subtractive
- smart assembly
- combined processes

TRL target:

- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

- **research (1-2-3)**
  - **basic principles**
  - concept and application formulation
  - concept validation
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- lack of a predictive model
- workcell management
- **load bearing properties**
- on-site installation
- on-site assembly
- resource consumption
- scalability
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- **development of new materials**

1. Tool making - the various parts for testing the programming at Taubman College. 2. Tool making - fixture assembling. 3. Programming (left) - digital simulation of the extrusion process. The extruder remains in place while the robot lowers. Installing (right) - physical setting. 4. Material preparation and extrusion testing - first outcomes. 5. Pugmill construction. 6. Filling the tubes of clay. All credits: Mark Meier.

Description

Linear extruder tool. The tools that can be used for the robo clay extrusion are available on the market. A popular platform to purchase a 1000/2000/4000 ml clear pipe is 3D potter. The electronic controller is usable via Grasshopper and/or the robot Programmable Logic Controller (PLC). It comes with a stepper motor, a gearbox to convert the rotary motion into linear motion, a plunger and gasket to seal against the two supplied 7,5 cm diameter by 60 cm long tubes. A few objectives governing the electronics are: - to set touch screen interface to easily control the extruding mode and speed; a 4D System was used. The interface uses a single pin on the Arduino and the interaction processing is handled directly on the display. There is also a user interface builder program that's user friendly for the interaction creation; - to limit the current drawn by the motor to less than 3 amps; - to control it via an Arduino microcontroller in order to write fully customizable codes.

Motor controller. A motor controller (TB6600 4A 9-42V Stepper Motor Driver) is used to limit the current. Allowing the extruder motor to draw too much power makes it push too hard which can result in bending the ball screw. The power supply/transformer used was a Minger Power Supply 24V 6A Power Adapter Transformer. The extruder ships with a stepper motor. The key properties are: model No.: JK57HS56-2804, step Angle 1.8, current per Phase 2.8, resistance per Phase 0.9, inductance per Phase: 2.5, holding Torque: 1.26, detent Torque 350. The motor is programmed using the AccelStepper Library from AirSpayce. This is a freeware programming interface for stepper motors which supports accelerating and decelerating as the motion starts, stops, and changes speed.

Fixture construction. A fixture is designed and built to hold the extruder. It is suitable for the robot axis limits. It's easier for the robot to reach up high rather than move around down low. The fixture was made of poplar boards and some birch plywood using a table saw, a chop saw, a plunge router, as well as chisels and planes. Basic half-lap joint are used for the base with the grooves for the plywood which brace the column. Mortise and tenon joint on the horizontal member are at the top. Four of these parts cut from scrap plywood hold the extruder to the fixture. They get flipped over and glue on top of one another. The pockets, partial depth cuts, are for screw holes and a gasket. A rubber gasket inside provides a secure grip to the tube. The plate is secured to the robot. On top of that is a piece of melamine that can be easily lifted off the robot to support the object as it dries. The robot moves beneath the tool. The extruder never moves laterally or vertically as all movement is taken up by the robot.

The robot code was developed with Rhino, Grasshopper, and Kuka|prc. The steps are:
1. convert the 3D model to print to a mesh because that contours much more reliably;
2. contour (section) the mesh model. These are the curves the extruder follows;
3. reverse the vertical direction so printing happens bottom to top;
4. divide each contour into points for the robot to move to;
5. move the robot to each point.

The procedure requires one to: assign the object to print, indicate the coordinates of where the extruder is relative to the robot base (which is measured with the robot itself), and choose the thickness of the layers and the number of divisions of each layer. The robot's speed is also variable. It typically moves in the range of 10-20mm/sec. The simulation shows the process. The fixture holds the extruder in place - it never moves. The robot provides all the motion. It starts at the bottom of the vessel and adds layers to get to the top. It looks upside down in the simulation but because it prints from top to bottom on the platter the result is right-side up. Ceramic material preparation. The material that is extruded is a low grog, cone 6 clay body. Adding 15 ounces of water to the 25# bag of clay helps soften it. A good technique is to slice the clay vertically into quarters, put in micro-fiber towels in the gaps, and add water. Once the water has absorbed (over the course of 1 or 2 days) it's ready to be loaded into the extruder cylinder, possibly using a pugmill. The clay has to be softened to work with the extruder. To get more moisture into the clay and make it even softer, it's recommendable to cut it into quads, vertically and then put towels into the joints. Then add 15 ounces of water to the 25# bag and let this soak in for at least two days, rotating the bag a few times so all the clay gets exposed. When done the clay is much softer and appropriate for the extruder.

Extrusion testing. The first thing made for testing was a coil pot cylinder. The coil diameter is 6mm. There's a vertical step up of the robot from layer to layer of 5mm. The speed of the robot is 20mm/second. The speed of the extruder is about 800 steps per second. All those factors need to be coordinated. The next test was a simple twisting, triangular form. The continuity of the clay extrusion helps it maintain structural integrity. The adhesion from layer to layer is also quite good right away. The softened, damp clay helps in this regard. The layers of clay are generally uniform and consistent in width. The clay gets a bit thicker at the corners. This is because the robot slows down as it approaches the corner so it can reach the corner position accurately. There's a setting in the robot programming to introduce less positional accuracy but more speed consistency (the C_DIS value). In this test the setting was 1mm. That means when the robot gets within 1 mm of the desired position it moves on without having to get there exactly. This allows it to hold its speed better. More experimentation is needed with this setting to balance the two concerns. An issue is how to handle the seam. It is the point on the form where the robot moves vertically to step up to the next level. One solution is to put the lift on a cusp or change in direction of the form. In this way the seam appears more integrated with the form.

Getting the clay into the tube via a pugmill. A pugmill is used to unify the moisture content in clay and remove air from it. It uses a powerful motor to push the clay through a set of grates which divide the clay into thin rods. These are then pushed through a vacuum chamber. This pulls all the air bubbles out of the thinned clay tubes. The clay is then unified back into a solid mass which is extruded through the end of the mill. A fixture holds the tube to the pug mill. It goes together with glue and screws. It holds the tubes tightly. The pugmill is used to load up air-free clay. It takes around 2 hours to load 10 tubes of clay.

Results and refinements. After all the preparation, it was time to extrude some vases. The extruder is fixed in space. The robot draws the helix beneath it. The basic problem is how evenly the extruder runs at startup. That wavy pattern one can see in some pots is uneven initial clay output. We can start at the center of the pot and work outward. That'll put the uneven flow on the inside. There are two floor layers so the second one will cover the first. It may be time to mount the extruder on the robot and see how that can improve things. This has some potential for better adhesion from layer to layer when cantilevering.

Feedback

This project was used as litareture review for the experiment of this dissertation.

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Sagrada Familia

Project data

University / research center: Administration of Barcelona, Royal Melbourne Institute of Technology (RMIT)
Project team: executive architect and researcher Mark Burry
Research program: Sagrada Família Basilica Foundation
Equipment: 2 1⁄2 D robots, hybrid digital-analogue tools, and 7-axis robots
Digital tools: algorithm and parametric design for geometry reconstruction and robo-programming
Year: 1989- ongoing

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- **exterior walls**
- roof
- **interior walls**
- **interior floors**
- cladding
- **decoration**
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- **stone**
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- **parametric design**
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- **subtractive**
- **smart assembly**
- combined processes

TRL target:

- process innovation
- **tool (machine or end-effector)**
  - visual sensing
  - tactile sensing
- **design outcome**

TRL advancement:

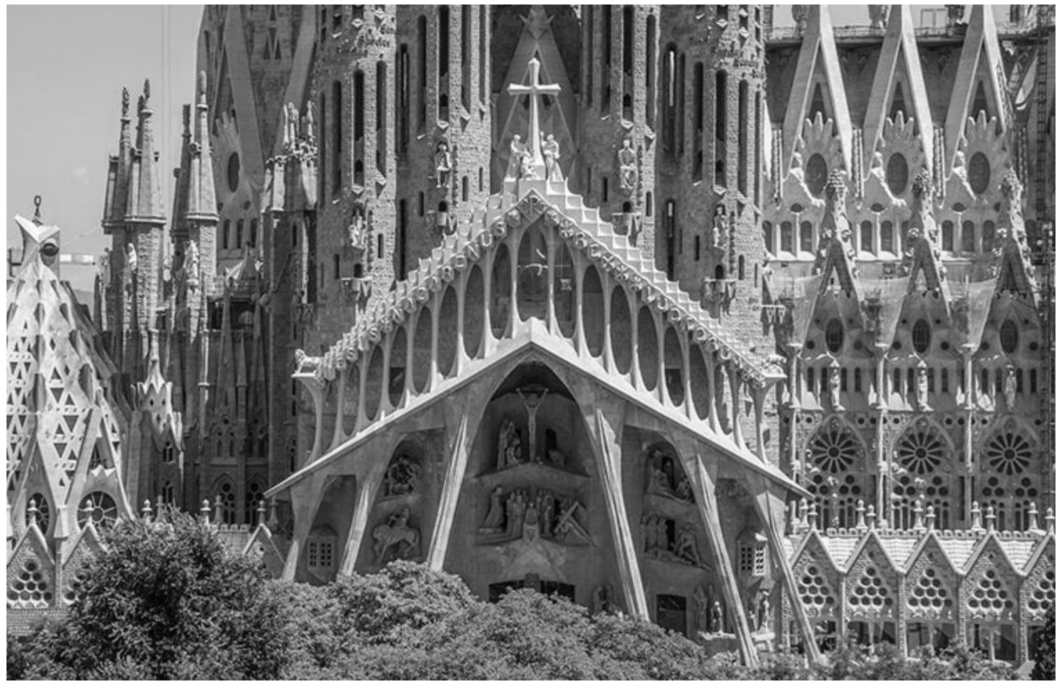
- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation

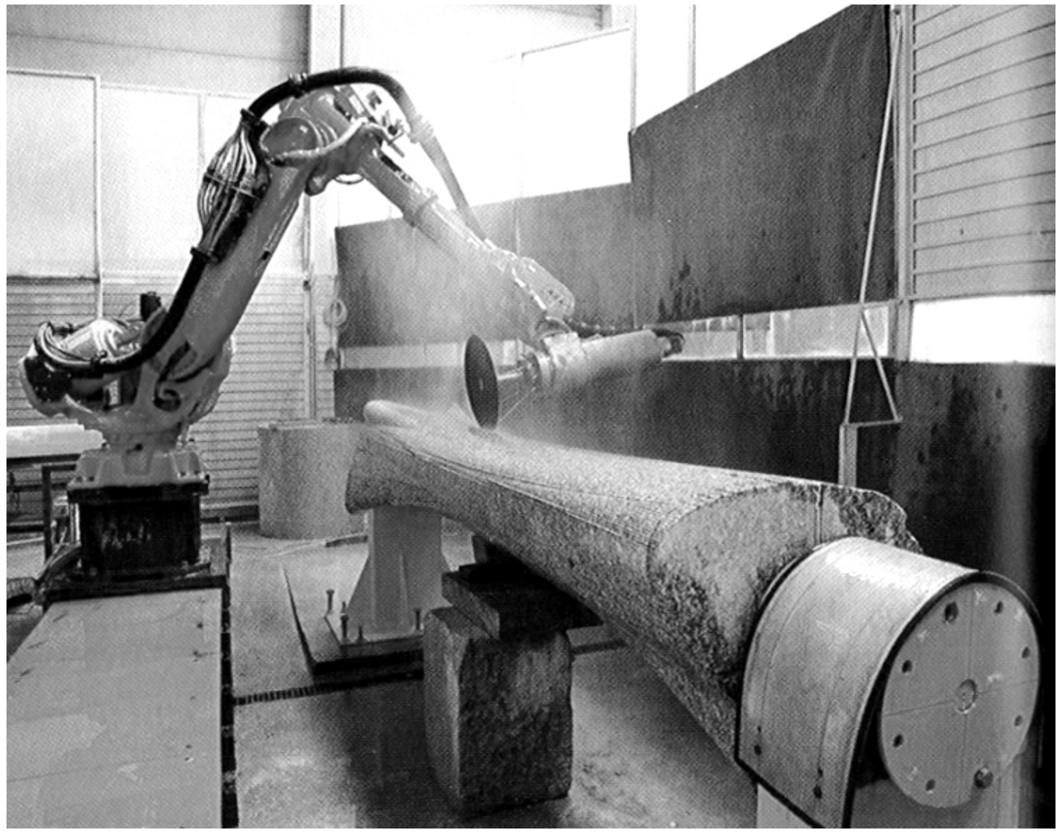
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot

- **deployment (7-8-9)**
  - early stage implementation
  - release version
  - **extensive implementation**

Technical complexities:

- **digital process management / modeling**
- **production process management**
- uncertainty management
- lack of a predictive model
- workcell management
- load bearing properties
- **on-site installation**
- **on-site assembly**
- resource consumption
- **scalability**
- **interface of the elements produced with complex surfaces**
- level of detail of the outcome
- development of new materials





Description

The continual construction of the Sagrada Familia Church in Barcelona is an example of how computational design workflows and the production of complex geometries has evolved over more than two decades, advancing the volumetric integration of an architectural pre-existence. Due to the size and complexity of the building elements, the construction phase of the Sagrada Familia, still in progress, requires the programming of human, technical, and economic long-term resources. The work of the professionals involved is evidence of the optimization of processes and the application of high technology to geometrically define and carve massive stone elements to complete the formal unity of a high historical value artifact. The updating of production methods and the use of increasingly sophisticated tools is a consequence of the customization desired by Gaudi of each architectural unit making up the construction system of the Sagrada Familia. The most recent design-related innovation employed the use of a 7-axis robot for subtractive stone processing. he possibility of the mechanical arm to slide on a track allows the robot to operate with large material units such as a column 9 meters high is defined only by three parts: base, shaft, and capital.

Feedback

The use of robotics has demonstrated the possibilities of accuracy of digital workflows for heritage interventions. It is not excluded that in the next few years industrial machines will be accessible to such an extent that they will be more widely distributed within the Barcelona construction site. Additionally professionals will use AR to simulate virtually the missing geometries before proceeding to manufacture and further minimize potential dimensional deviations. The Sagrada Familia project defines a milestone in the state of the art of large-scale robotic digital fabrication for several reasons: 1) it is a large-scale application of the most advanced digital tools; 2) it is a project that required the definition of an iteration of complex workflows, starting from digital computation to CAD-CAM transfer of intersected surfaces such as helicoids, hyperbolic paraboloids, and hyperboloids of revolution; 3) it employed robotics for large-scale production of customized architectural elements. Moreover the Sagrada Familia case study, from the point of view of cultural legitimacy, provides a multi- decade reconstruction as a component of dialogue between digital manufacturing and craftsmanship for a culturally relevant testbed.

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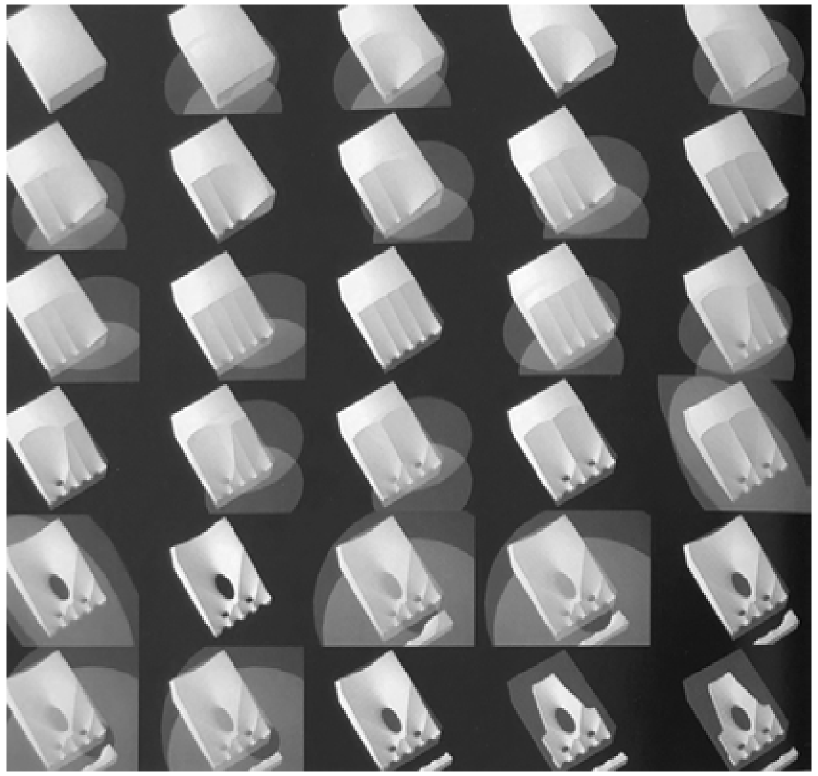
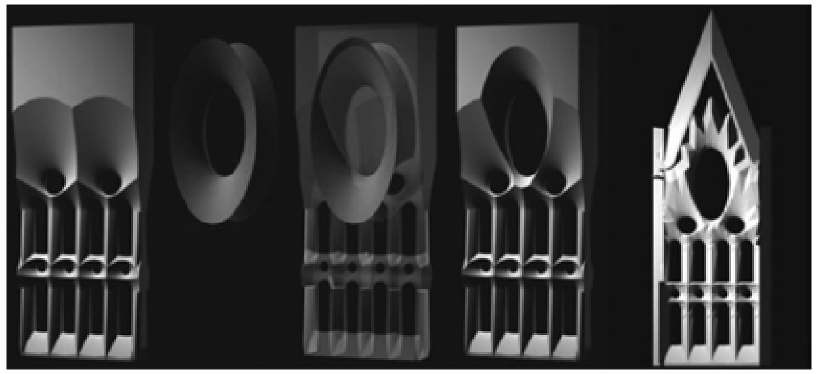




Computer vision

Mobile robotic brickwork

Project data

University / research center: ETH Zurich, Chair of Architecture and Digital Fabrication
Project team: Kathrin Dörfler, Timothy Sandy, Markus Giftthaler, Fabio Gramazio, Matthias Kohler, and Jonas Buchli
Research program: work carried out by Gramazio Kohler Research and AgileDexterous Robotics Lab with the support of the Swiss National Science Foundation
Equipment: IF, In situ Fabricator (mobile robot platform)
Digital tools: commands are sent via a Python interface within Grasshopper to the ROS nodes of the robot for base movement. ABB Robot Control Software is also used for arm manipulation procedures
Year: 2006

Scale:

- technological unit
- **technological subsystem**
- architectural system

Project applications:

- **exterior walls**
- roof
- **interior walls**
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- **low-engineered**
- high engineered

- **ceramic**
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- **parametric design**
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- **smart assembly**
- combined processes

TRL target:

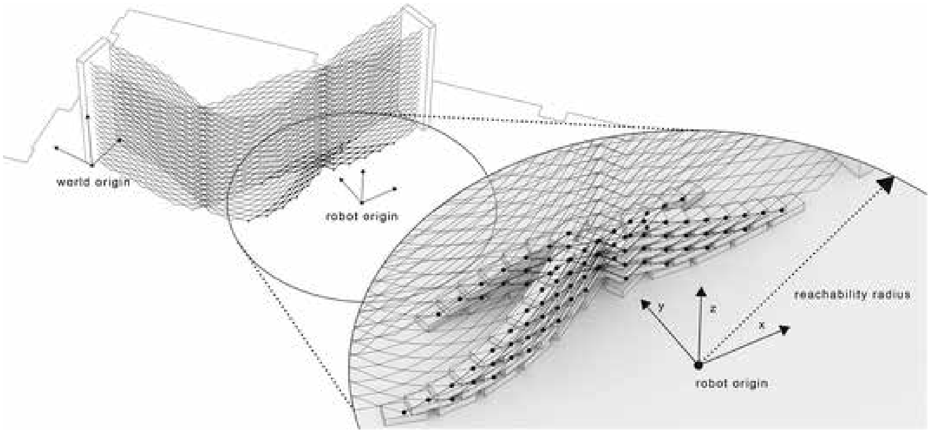
- **process innovation**
- **tool (machine or end-effector)**
  - **- visual sensing**
  - - tactile sensing
- **design outcome**

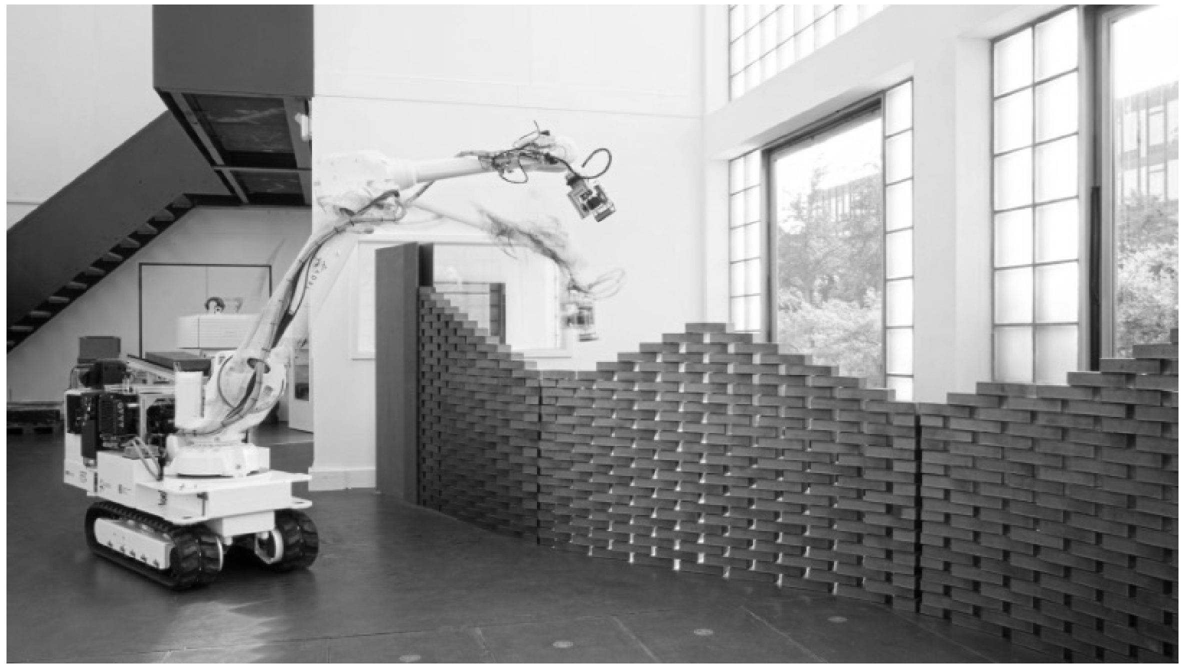
TRL advancement:

- research (1-2-3)
  - - basic principles
  - - concept and application formulation
  - - concept validation
- **development (4-5-6)**
  - - experimental pilot
  - **- demonstration pilot**
  - - industrial pilot
- deployment (7-8-9)
  - - early stage implementation release version
  - - extensive implementation

Technical complexities:

- **digital process management / modeling**
- production process management
- uncertainty management
- lack of a predictive model
- workcell management
- load bearing properties
- **on-site installation**
- on-site assembly
- resource consumption
- **scalability**
- interface of the elements produced with complex surfaces
- level of detail of the outcome
- development of new materials





Description

The project consists of a laboratory test to perform a construction process of the exterior envelope of a building using a mobile robot. A parametrically designed dry brick wall was built indoors in a semi-autonomous way to perform a concept test for a real application. The research team developed the robotic tool so that it could perform complex tasks through the support of sensors, control hardware, and computing systems. The software-hardware collaboration allows the robot to locate itself in space and understand the geometry of its environment. As a result, the robot is able to measure dimensional tolerances and assemble construction components with precision in space, including the relationship to pre-existing elements that constitute a constraint in the workcell. The IF (In situ Fabrictor) contains in its hardware all the installations necessary to have complete autonomy of action. Human interaction is limited to software interface management. In addition, the robot does not require external reference systems for site configuration. A customized TCP-IP implementation allows online control of the robot arm and base. Commands are sent through a Python interface in Grasshopper to the robot nodes for base movement and through ABB Robot Control Software for arm manipulation. The visual sensing system allows to generate a feedback loop process for which the input data is updated in real time allowing to recalculate the kinematics accordingly.

Feedback

This experiment attempts to advance research on automatic systems to facilitate site operations. The robot designed by the research team is autonomous, equipped with sensors able to filter changes in the field of vision in real time and able to interact with obstacles. The future goal is to scale-up the process, trying to update the construction industry with new construction approaches for architecture adaptable to the robotic assembly of components directly on-site. The dry brick building was built between two pillars. The tectonics at the base of the masonry prototype is based on simple laying logics, with traditional material and dimensions. This choice was made because of the need to solve basic technical problems with adaptive control strategies before exploring the design and its technological units. The experiment also opens up questions about the possibility of robotics to operate in more complex contexts where tasks overlap geographically and sequentially. Future research will be fundamental to move towards integrated and controllable construction processes.

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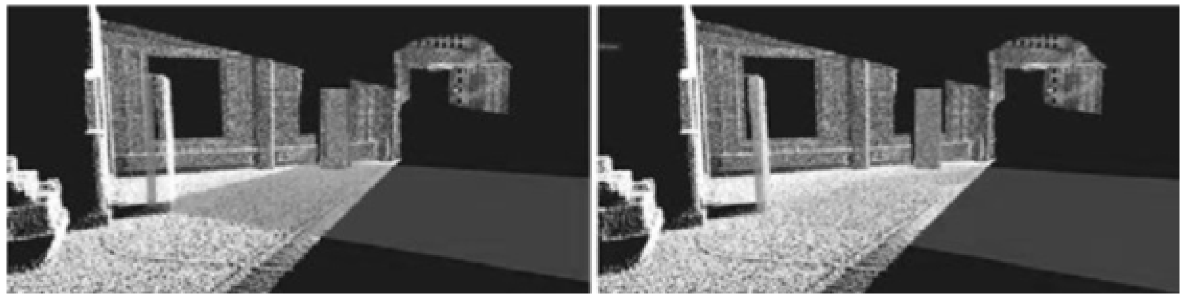
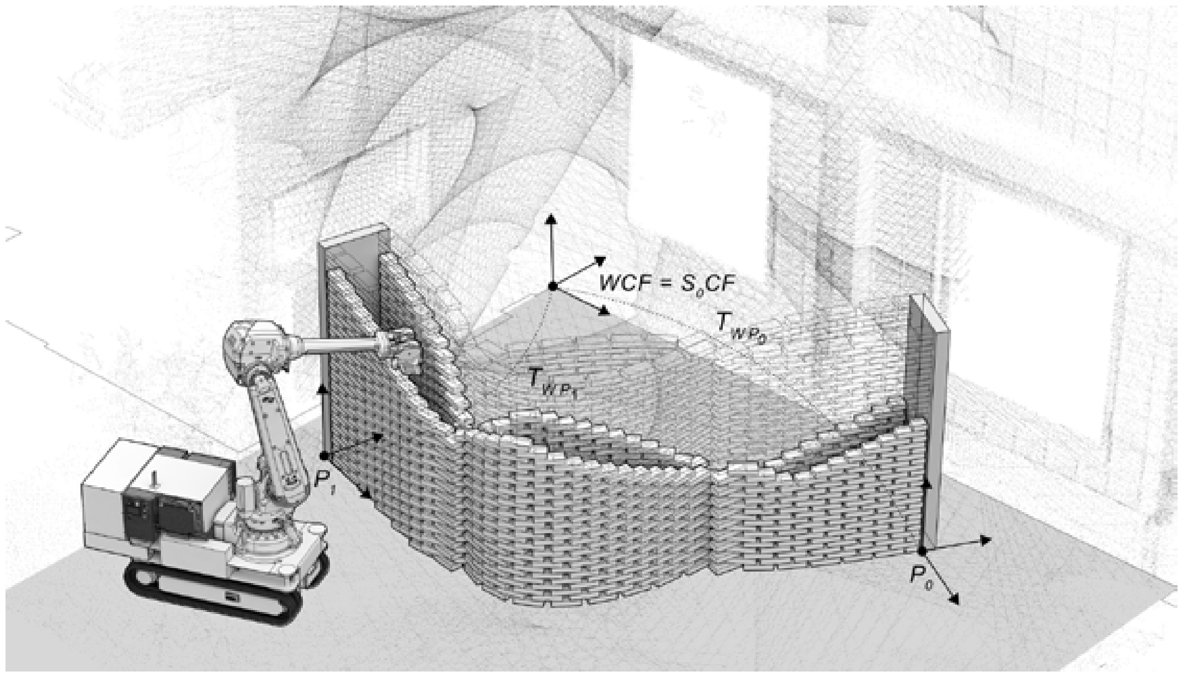




In situ robotic fabrication - The Fragile Structure

Project data

University / research center: Gramazio Kohler Research, ETH Zurich
Project team: Fabio Gramazio, Mattias Kohler, Dr. Volker Helm, Dr. Ralph Bärtschi, Tobias Bonwetsch, Selen Ercan, Ryan Luke Johns, Dominik, and Weber
Research program: EU FP7 Programme – Echord
Equipment: ABB IRB 4600 on mobile platform, and Universal Robot UR5
Digital tools: customized programming for computer vision and material sensing
Year: 2012

Scale:

- technological unit
- **technological subsystem**
- architectural system

Project applications:

- **exterior walls**
- roof
- **interior walls**
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- low-engineered
- high engineered

- ceramic
- **wood**
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- **parametric design**
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- **smart assembly**
- combined processes

TRL target:

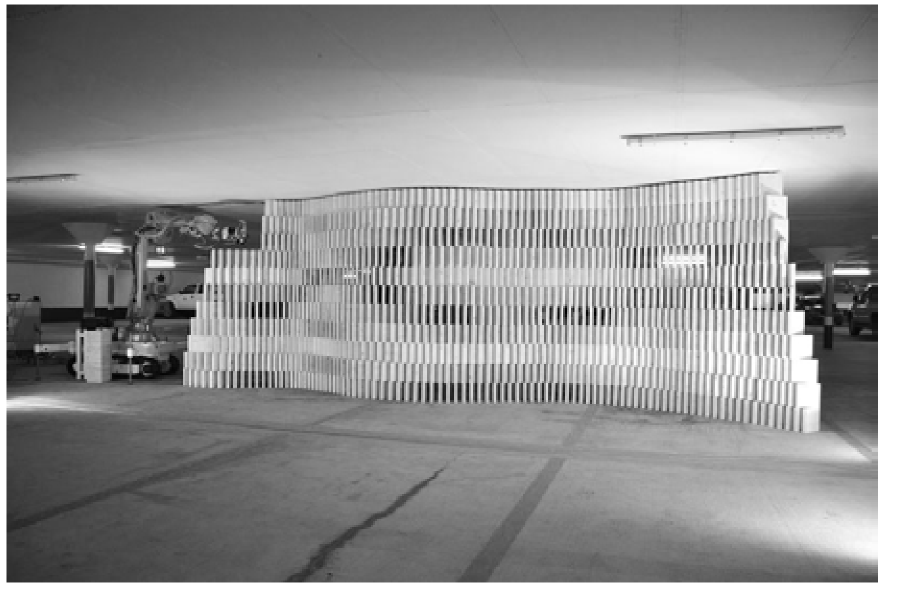
- process innovation
- **tool (machine or end-effector)**
  - visual sensing
  - tactile sensing
- design outcome

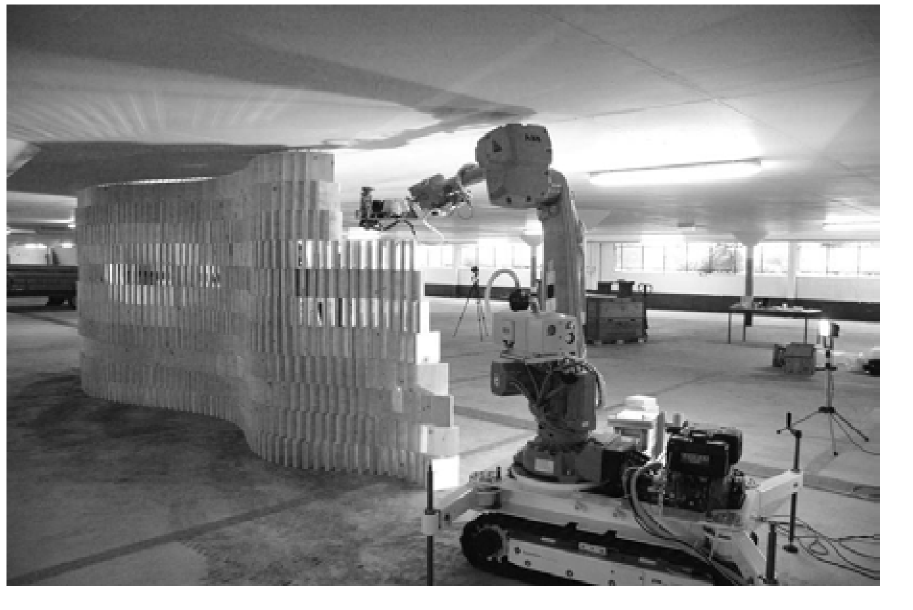
TRL advancement:

- **research (1-2-3)**
  - basic principles
  - concept and application formulation
  - concept validation
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- lack of a predictive model
- **workcell management**
- load bearing properties
- on-site installation
- on-site assembly
- **resource consumption**
- **scalability**
- **interface of the elements produced with complex surfaces**
- level of detail of the outcome
- development of new materials





Description

The theme explored during this research is the use of industrial robots on the construction site. To this end, the researchers have developed advanced software and hardware, combining hand-built elements with the original robot. The Fragile Structure is a research prototype consisting of a wall assembled with wooden elements between floor and ceiling. The structure was dry-assembled, through a gripper that grabbed the construction units and leaned on each other until a sinuous geometry was defined. The robot is set up in such a way as to acquire information to recognize its position, the surrounding environment, and its components. The research and development of robotics are advanced by the ECHORD project within the Seventh Framework Programme of the European Union in order to create new use cases and develop the technologies necessary for the advancement of the state of the art. The future hypothesis is to innovate the construction industry by creating new fields of application for architects and the robot industry.

Feedback

There are several aspects of this experiment that are relevant to this research. First is the construction of the prototype within two horizontal constraints. In the academic state of the art for the realization of works customized by robotic process usually workcell is considered as an operational limit. In this case, instead, the machine is forced not to perform the kinematics by looking down, but by moving in parallel with the work under construction. This aspect is relevant because in this way we try to bring laboratory research closer to the complexity of the construction site reality. Moreover, the robot is equipped with a feedback loop system that allows the toolpath to be updated in response to changes in the real conditions of the work progress. In order to obtain an efficient visual sensing system, the researchers have developed an algorithm able to collect geometric information through a camera installed on its head and transfer it to the TCP, tool center point, i.e. the position where the actual action takes place. The robotic system must meet construction tolerances and be able to adapt to changing conditions independently. This technical exercise, carried out in 2012, encouraged not only research centres but also European industries and framework programmes to invest in the direction of site robotics.

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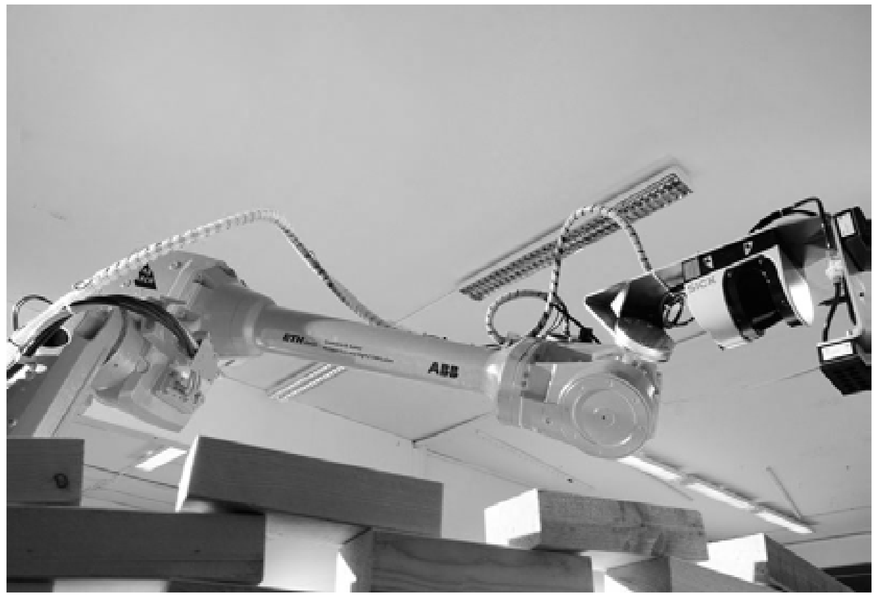

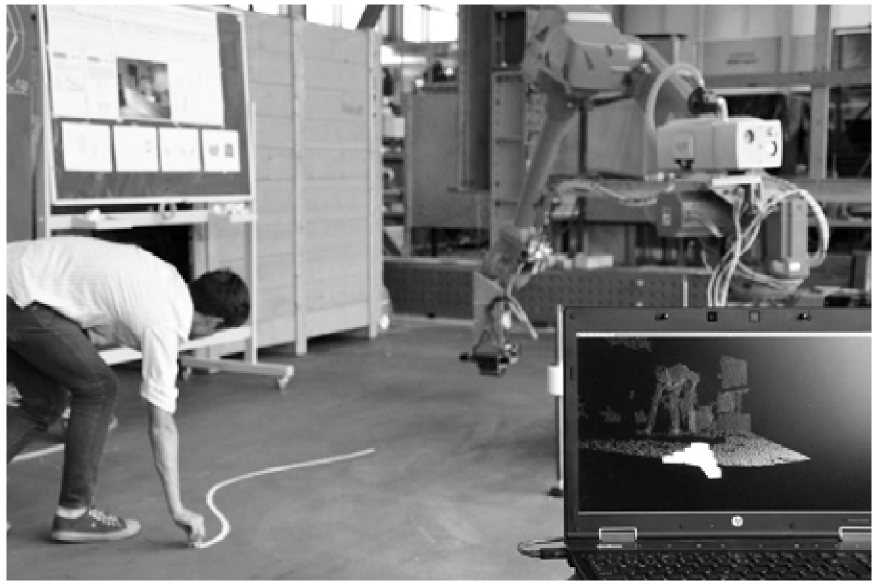

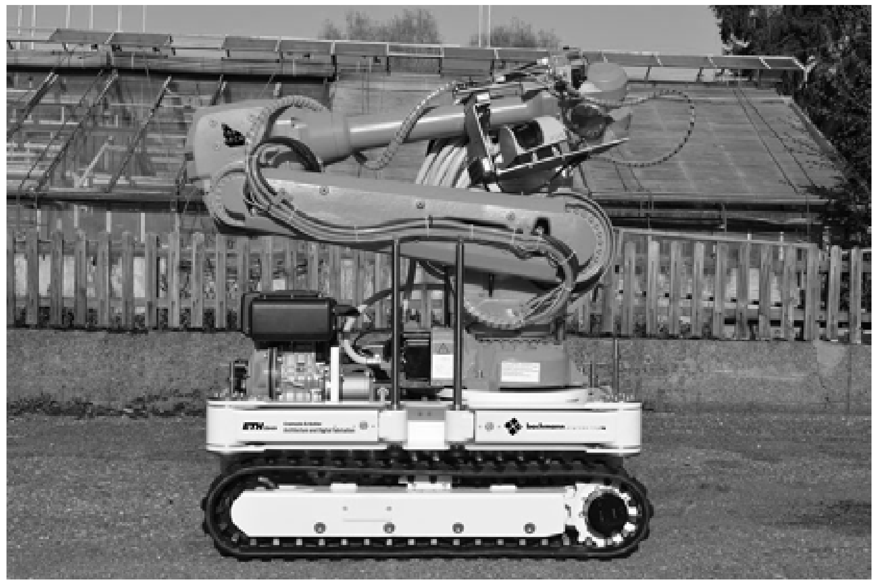

Minibuilders

Project data

University / research center: Institute for Advanced Architecture of Catalonia (IAAC)
Project team: Saša Jokić, Petr Novikov, Shihui Jin, Stuart Maggs, Dori Sadan, and Cristina Nan
Research program: Advanced Architecture Group
Equipment: customized mobile robot
Digital tools: customized programming and scripting
Year: 2016

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- **exterior walls**
- roof
- **interior walls**
- interior floors
- **cladding**
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- low-engineered
- **high engineered**

- ceramic
- wood
- **stone**
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- **3D modelling**
- parametric design
- **algorithmic scripting**
- virtual simulation

Fabrication process:

- **additive**
- subtractive
- smart assembly
- combined processes

TRL target:

- process innovation
- **tool (machine or end-effector)**
  - **- visual sensing**
  - tactile sensing
- design outcome

TRL advancement:

- **research (1-2-3)**
  - basic principles
  - concept and application formulation
  - **- concept validation**
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- **uncertainty management**
- lack of a predictive model
- workcell management
- load bearing properties
- on-site installation
- on-site assembly
- **resource consumption**
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials

Description

The IAAC in Barcelona through this experiment investigated the potential of additive production on the architectural scale. The project team developed three robots capable of working independently, but coordinated, towards a shared goal. Each robot is designed to perform a different task, linked to the different phases of construction, towards the shared realization of a single structural result. Each robot is connected to sensors and a local positioning system. These feed the data in real time into a customized software that allows to control the movement of the robots and the deposition of the output material. The material chosen for the realization of the research prototype is quick-hardening artificial marble. The three robots work sequentially: 1) Robot base. The first robot lays the first ten layers of material to create a foundation impression. Inside the robot are mounted sensors that control the direction, following a predefined path. Traveling in a circular path allows a vertical actuator to incrementally adjust the height of the nozzle to obtain a smooth, continuous, spiral layer. The advantage of placing the material in a continuous spiral is that it allows a constant flow of material without having to move the nozzle upwards at one layer intervals. 2) Grip Robot. The second robot, it attaches itself to the footprint of the foundation. Its four rollers attach to the upper edge of the structure allowing it to move along the previously printed material, depositing several layers. 3) Vacuum Robot. The third robot deposits material on the outer surface, enhancing its structural properties.

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Robotic softness - adaptive carving

Project data

University / research center: Bartlett School of Architecture, University College of London
Project team: PhD candidate Giulio Brugnaro and supervisors Prof. Bob Sheil and Dr. Sean Hanna
Research program: the project is part of ongoing Ph.D. research conducted within the framework of the InnoChain Training Network, supported by the European Union's Horizon 2020 research and innovation program under the Marie Sklodowska-Curie grant agreement No. 642877
Equipment: small industrial robot (KUKA KR6) equipped with a carving tool used by craftspeople and a system of motion-capture cameras arranged around the workpiece (OptiTrack mocap)
Digital tools: Rhino3D / Grasshopper / programming plug-in
Year: 2017

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- exterior walls
- roof
- interior walls
- interior floors
- **cladding**
- **decoration**
- scale model

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- **mono-material**
- multi-material

- **low-engineered**
- high engineered

- ceramic
- **wood**
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- parametric design
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- smart assembly
- combined processes

TRL target:

- process innovation
- **tool (machine or end-effector)**
  - **- visual sensing**
  - - tactile sensing
- design outcome

TRL advancement:

- **research (1-2-3)**
  - - basic principles
  - - concept and application formulation
  - **- concept validation**
- development (4-5-6)
  - - experimental pilot
  - - demonstration pilot
  - - industrial pilot
- deployment (7-8-9)
  - - early stage implementation release version
  - - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- uncertainty management
- lack of a predictive model
- workcell management
- load bearing properties
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials

Description

This experiment develops a method to train an adaptive robotic system for subtractive production with wood. The method is based on the feedback loop workflow, which allows you to explore materials through learning the machine. The methods were evaluated in a series of tests in which the manufacturing parameters for simple wood cutting operations with chisels and gouges were developed. The results suggest potential benefits for non-standard manufacturing methods and a more cost effective use of material. Robo-training combines the recording of qualified experts performing subtractive operations with a range of traditional wood carving tools together with stand-alone robotic carving sessions. For each recording session, the combination of different sensing strategies, such as motion capture cameras and force-feedback sensor, allows manufacturing data to be collected simultaneously with the execution of the notching operation and compiled into a continuously updated data set. The input parameters are: tool / workpiece angle, tool angle / grain direction, robot feed rate, cutting depth, and cutting length. The data recorded on the machined material are: depth, length, and width of cut. Both the recorded toolpath and the robot toolpath are composed of a sequence of reference frames, each of which is recorded as a single input in the total data set.

Feedback

The operating method is based on a series of data set processing procedures, in which the instrumental and material knowledge, acquired both by qualified human experts and by robotic carving sessions, is transferred into an interface that makes this knowledge available to the designer. Robotic softness is an advanced experimentation that through robotic manufacturing and machine learning hypothesizes possible future explorations to explore new production opportunities through innovative design workflows. The experiment shows that it is possible to simulate the results of subtractive operations on the basis of a dataset of manufacturing parameters and use this instrumental knowledge to perform iterations between robotic toolpath data and geometry prediction. The experiment focused on two different workflows for generation, examining whether it is better for the robotic system to learn from an experienced human expert or from autonomous training sessions. The combination of human and robotic training was effective. The contribution of a human expert made it possible to collect data within an optimal manufacturing range, operating within a narrow range of parameters that excluded inefficient cuts. The deepening of knowledge in distinctly operational areas such as human manufacturing and industrial robotic production presented the opportunity to develop an approach for human-machine interaction that questions the industrial approach to production.

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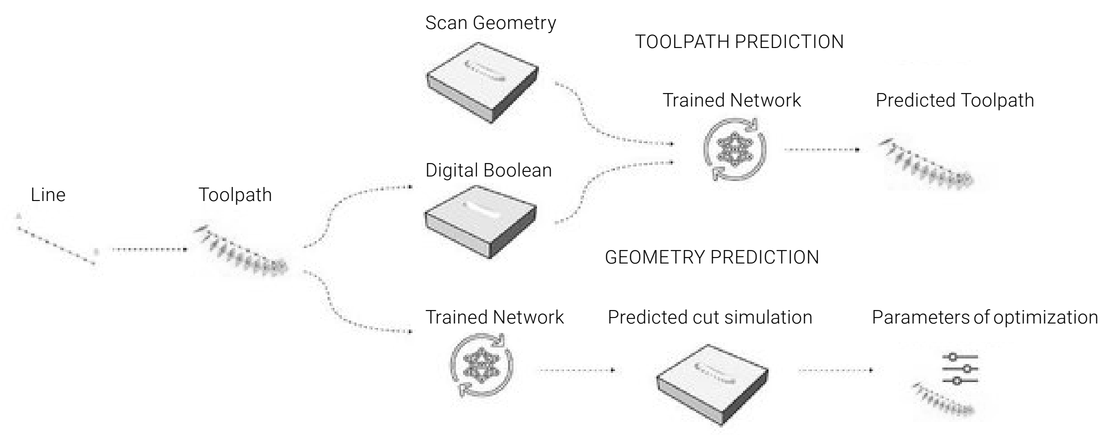
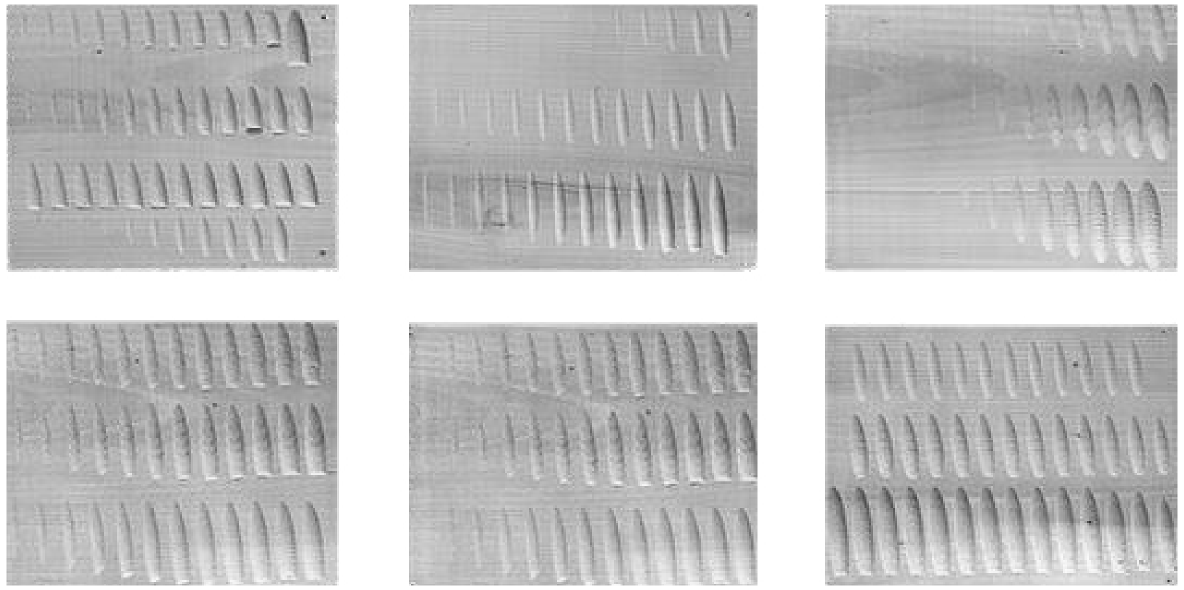




Mesh mould

Project data

University / research center: ETH Zurich - Gramazio Kohler Research
Project team: Fabio Gramazio, Matthias Kohler, Norman Hack (project lead Mesh Mould), Kathrin Dörfler (project lead In situ Fabricator), Dr. Nitish Kumar, Alexander Nikolas Walzer, Manuel Lussi, Maximilian Seiferlein, Dr. Jaime Mata Falcon, Julio Alonso Lopez, Dr. Tim Wangler, Lukas Stadelmann, Lex Reiter, Hannes Heller, Michael Lyrenmann, Heinz Richner, Philippe Fleischmann, and Andreas Reusser
Research program: the research and building project is pursued in the framework of the National Competence Centre of Research (NCCR) Digital Fabrication
Equipment: 6-axis ABB robot on mobile platform, equipped by sensors for feedback loop
Digital tools: customized programming and computer vision software
Year: 2016/2017

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- **exterior walls**
- roof
- **interior walls**
- interior floors
- **cladding**
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- mono-material
- **multi-material**

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- composite materials
- plastic
- **concrete**
- plaster

Design process:

- **3D modelling**
- **parametric design**
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- smart assembly
- **combined processes**

TRL target:

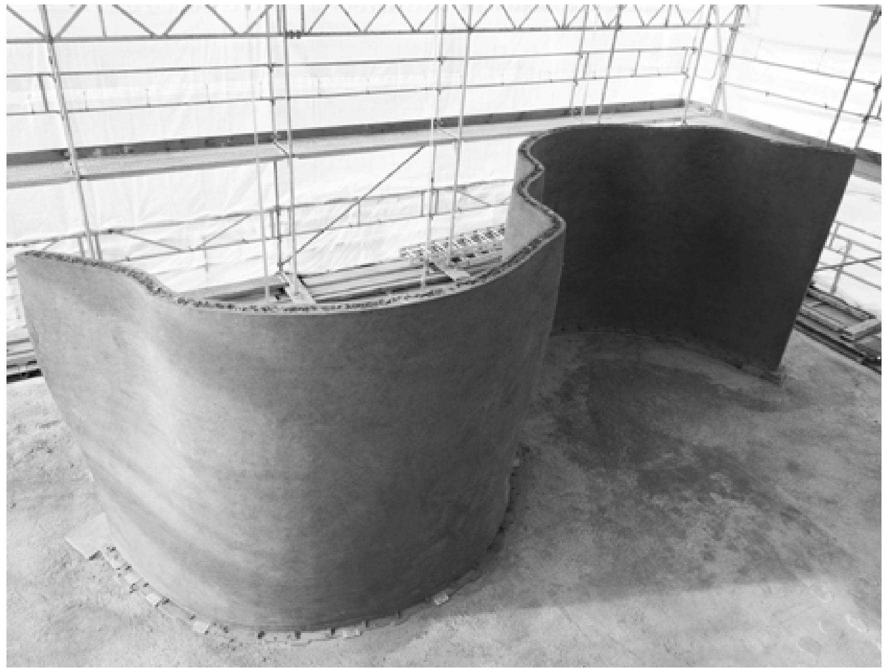
- **process innovation**
- **tool (machine or end-effector)**
  - visual sensing
  - tactile sensing
- **design outcome**

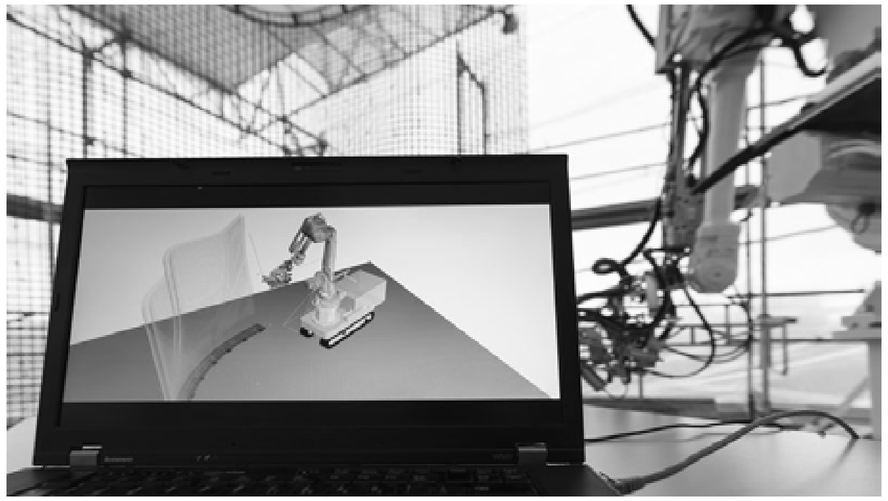
TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- **development (4-5-6)**
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- lack of a predictive model
- **workcell management**
- **load bearing properties**
- **on-site installation**
- **on-site assembly**
- **resource consumption**
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials





Description

Mesh Mould is a project developed at ETH Zurich in the context of the construction of Dfab House, the first housing unit to be built entirely by digital fabrication. The research product consists of the construction of a reinforced concrete wall with double curvature. The wall has a shape that improves the structural rigidity of the entire building system. The reinforcement reinforcement inside the wall is made by a six-axis robot on a mobile platform. The robot works with an end effector with which it bends and welds the 6mm diameter reinforcement rods. The detection and calculation system with which the robot is equipped allows the mesh to be constructed without external measuring devices. Before starting the robotic process, the wall footprint was determined on the floor by means of markers that serve as target reference points. A camera positioned on the end effector measures the tags and georeferences the robot in space via a calculation system. Two additional cameras monitor the accurate construction of the wire mesh. Concrete was then filled with a customized mix. The surface of the wall was finished by spraying.

Feedback

The construction approach introduced by the construction of the parametric reinforced concrete wall opens up a long series of innovations. First of all, the experiment was carried out in a real construction context, with all the resulting complexities. The robot and sensing system used is highly sophisticated and allows the machine to be aware of its construction within a non-standard work cell. Equally non-standard is the geometry of the wall, whose structural efficiency is integrated in the predictive digital model. The robot's feedback loop system is visual and tactile. To perform the smart assembly operations of the metal reinforcement, the robot must know exactly where the nodes to be welded are located and must be able to reconfigure its position based on the optimal distance from the target before performing the action. This example integrates construction site requirements, technical optimization of digital fabrication, and architectural quality.

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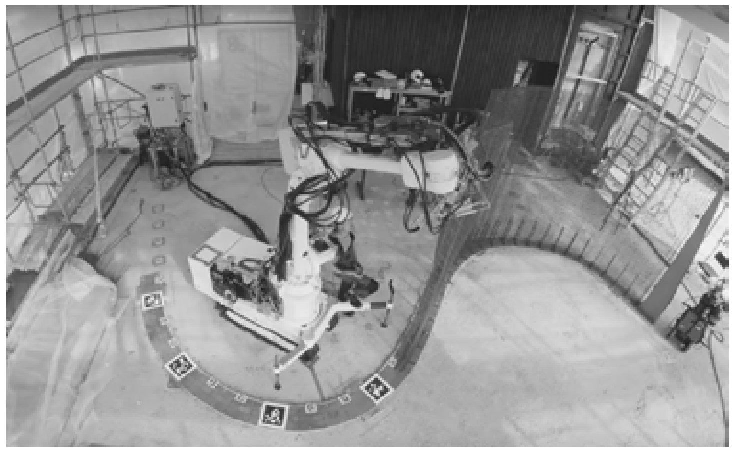
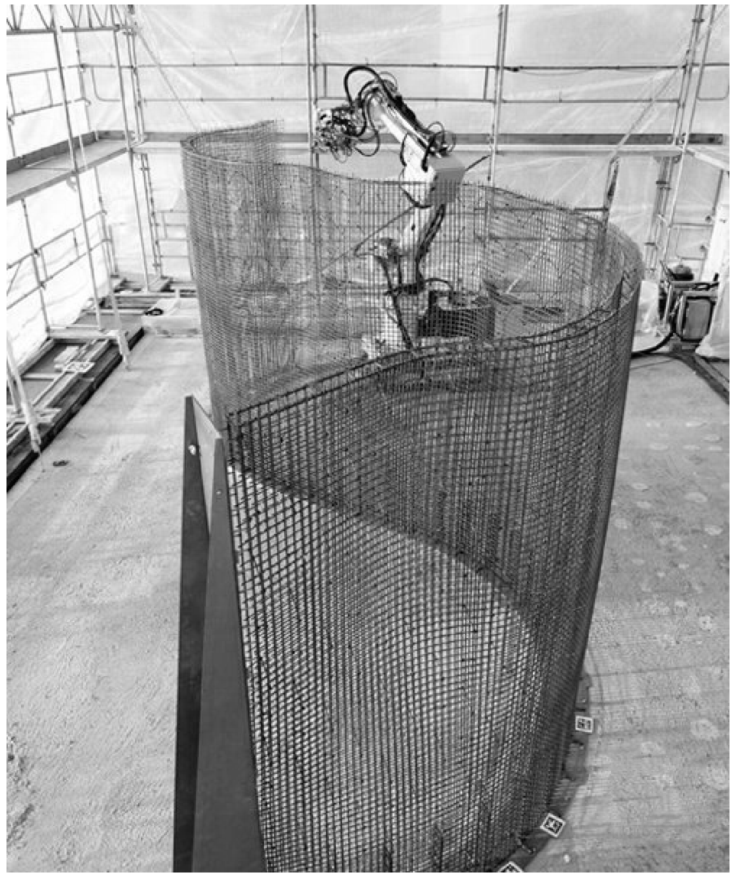




Spatial timber assembly

Project data

University / research center: ETH Zurich - Gramazio Kohler Research
Project team: Fabio Gramazio, Matthias Kohler, Lukas Stadelmann (ADRL), Michael Lyrenmann (RFL), Philippe Fleischmann (RFL), Andreas Thoma (Project Lead Fabrication), Arash Adel (Project Lead Computational Design), Thomas Wehrle (Project Lead ERNE AG Holzbau), Matthias Helmreich, Augusto Gandia, Gonzalo Casas, Matteo Pacher, Moritz Späh, Dr. Thomas Kohlhammer, Dr. Aleksandra Anna Apolinarska, Dr. Volker Helm, Dr. Ammar Mirjan
Equipment: 6-axis ABB robots on mobile platforms, equipped by sensors for feedback loop
Digital tools: customized programming and computer vision software
Year: 2016/2018

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- **exterior walls**
- **roof**
- **interior walls**
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- mono-material
- **multi-material**

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- composite materials
- plastic
- **concrete**
- plaster

Design process:

- **3D modelling**
- **parametric design**
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- smart assembly
- combined processes

TRL target:

- **process innovation**
- **tool (machine or end-effector)**
- **- visual sensing**
- **- tactile sensing**
- **design outcome**

TRL advancement:

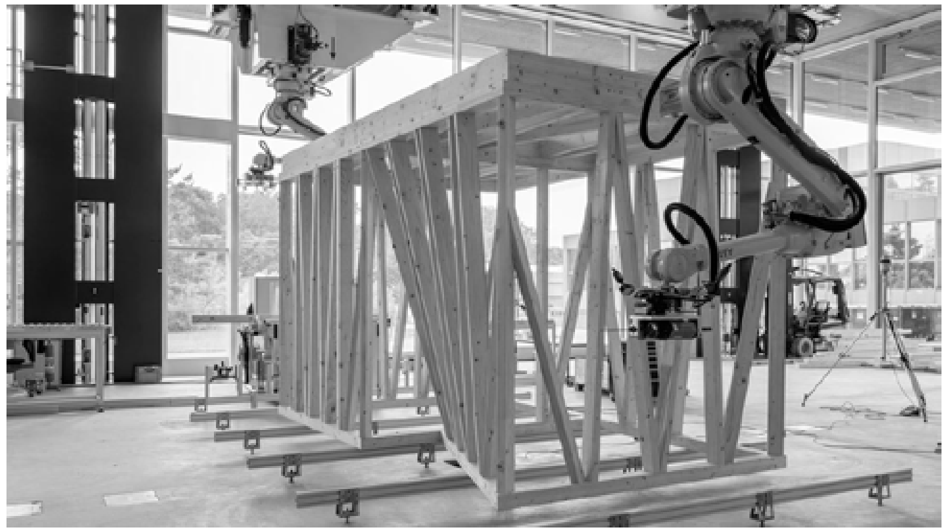
- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation

- **development (4-5-6)**
  - experimental pilot
  - demonstration pilot
  - **industrial pilot**

- deployment (7-8-9)
  - early stage implementation release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- lack of a predictive model
- **workcell management**
- **load bearing properties**
- **on-site installation**
- **on-site assembly**
- **resource consumption**
- **scalability**
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials



Description

The Spatial Timber Assemblies project focuses on the development of an innovative robotic manufacturing process for non-standard structural timber frames. The experimentation involved the use of multi-robotic cooperation on a building scale. Unlike traditional automated production systems, this example is oriented to find solutions to assemble customized wooden beams produced just-in-time and precisely positioned in space. The implementation of the robot allows the wooden modules to be composed in a smart way regardless of complexity, thus allowing a quick assembly on-site. As explained by the project team at Acadia, the key points of this research are: 1) automated just-in-time production 2) multi-robotic spatial assembly within a man-machine collaborative scenario 3) design integration through the computation of architectural requirements, manufacturing constraints, and assembly logic 4) validation of the possibility to scale the design for the construction of a multi-storey building.

Feedback

The method described was applied for the construction of the DFAB House, whose structure consists of exactly 487 beams, connected to each other by 2207 screws. The fabrication at the architectural scale was guided by fabrication-aware programming followed by validation in predictive simulation. The assembly sequence of the beams was determined according to the limits of the tools, i.e. the range of action of the robots. the robotic workcell is part of the computational feedback, which informs the project. The workflow was managed algorithmically, in an uninterrupted digital chain, from conceptual design to final materialization. This digital process is not based on sequential phases, but on dynamic construction. Although the whole process was entirely simulated before completion, the researchers found that the space for non predictivity is given by the material. Although the robotic fabrication and positioning of the wooden beams was accurate, the tolerances are the result of imperfections in the material. The cross-sections of the beams deviate from those desired depending on the quality of the wood. To handle these tolerances, one man fixed the beams with screws while one or two robots held them in place. This man-machine collaboration is an effective way to manage these tolerances and is expected to be supported by augmented reality in the future.

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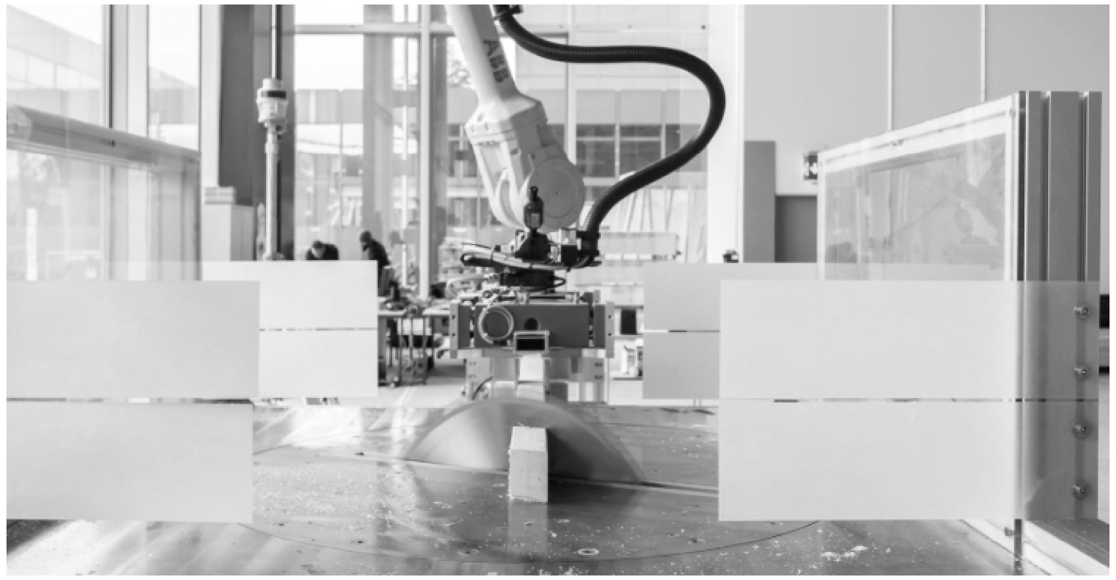

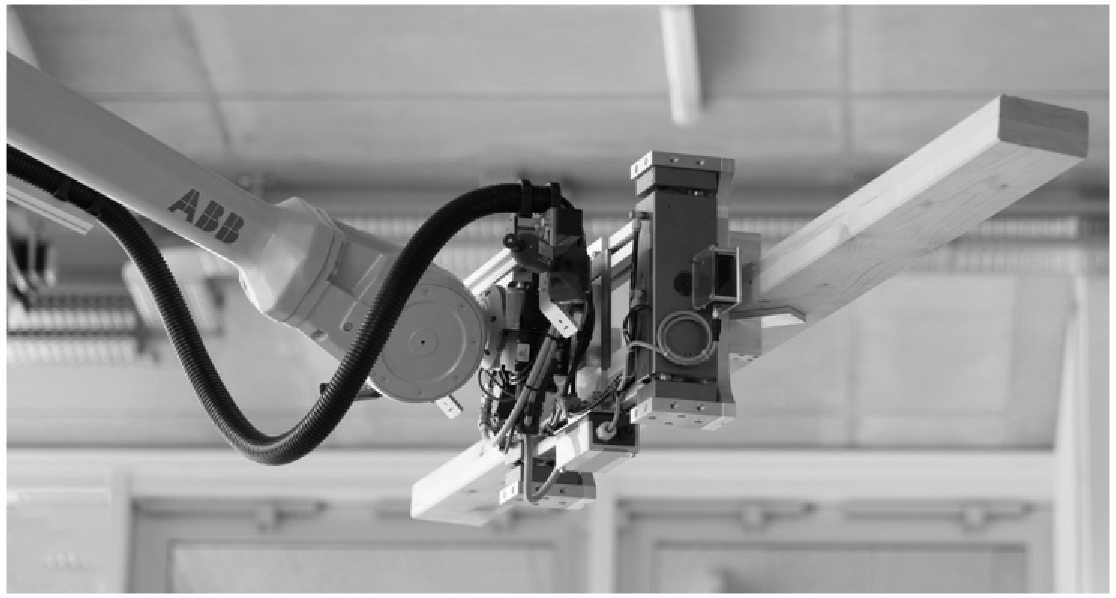

Re-configurable architecture system

Project data

University / research center:
Project team: Universität Stuttgart Institut fur Computerbasiertes Entwerfen und Baufertigung, ICD (Prof. Menges). Institut für Tragkonstruktionen und konstruktives Entwerfen, ITKE (Prof. Jan Knippers). Research Project of the Masters Course Integrative Technologies and Architectural Design Research (ITECH). ITECH M.Sc. Thesis: Miguel Aflalo, Jingcheng Chen, Behrooz Tahanzadeh Tutors: Dylan Wood, Maria Yablonina
Research program: Cyber Physical Macro Material
Equipment: autonomous drones, carbon fiber structure, and magnets
Digital tools: costumized scripting
Year: 2018

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- exterior walls
- **roof**
- interior walls
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

- mono-material
- **multi-material**

- low-engineered
- **high engineered**

- ceramic
- wood
- stone
- metal
- **composite materials**
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- parametric design
- **algorithmic scripting**
- virtual simulation

Fabrication process:

- additive
- subtractive
- **smart assembly**
- combined processes

TRL target:

- process innovation
- **tool (machine or end-effector)**
  - **- visual sensing**
  - **- tactile sensing**
- **design outcome**

TRL advancement:

- **research (1-2-3)**
  - basic principles
  - concept and application formulation
  - **concept validation**
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation release version
  - extensive implementation

Technical complexities:

- **digital process management / modeling**
- **production process management**
- uncertainty management
- lack of a predictive model
- **workcell management**
- load bearing properties
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- interface of the elements produced with complex surfaces
- level of detail of the outcome
- **development of new materials**

Description

Researchers at the University of Stuttgart designed a dynamic roof structure for public spaces that can be flexibly adapted to changing conditions. The construction system consists of hexagonal modules, called cyber-physical building blocks. These consist of a three-dimensional polyhedron frame made of carbon fibre-reinforced plastic. The sensors and electronics for the communication technology are integrated into the modules. The system can be divided into smaller sub-structures. A connector is built into each surface to transfer data and power between the module units. The drones are programmed to perform the construction process independently. They transport the construction modules at altitude. They are assembled by simple contact and consolidated through magnets placed on the perimeter of each module. Based on the established instructions, the flying object calculates a flight path for the transport of certain units to a new position. This dynamic and autonomous construction system is programmed to collect, through computer vision, information on changes in spatial conditions. The structure can therefore learn from its users. Based on the presence of groups of people, the geometry of the roof adapts independently, with the aim of better shading the users. During the development, portability, load capacity, cost, weight, energy consumption and aesthetics were taken into account during the development.

Feedback

The tectonics of the construction system used is defined by intelligent digital materials, integrated with an automated assembly method. This methodology can be used as a cyber-physical architecture in situations that adapt to temporary and highly adaptable conditions. The project demonstrates the functioning of an automated system that emerges as an architectural system open to programming and future development. The physical adaptability of the system and the programmability makes the system compatible with possible applications integrated with AI. The advances in artificial intelligence makes it possible to envisage a future in which buildings adapt physically and geometrically to variable internal and external conditions. The introduction of such systems in an architectural context requires a significant rethinking of architectural design methods towards an architecture based on dynamic behaviour, focusing on continuous post-occupancy design. This architecture forms a highly disruptive notion considering the current linear sequence of design, construction and occupation. Through the ability to continuously rebuild itself, the system also challenges established ideas of digital robotic manufacturing in architecture. In contrast to the traditional construction processes, physical flexibility and integrated intelligence open new possibilities in architecture for the adaptability and activation of public spaces.

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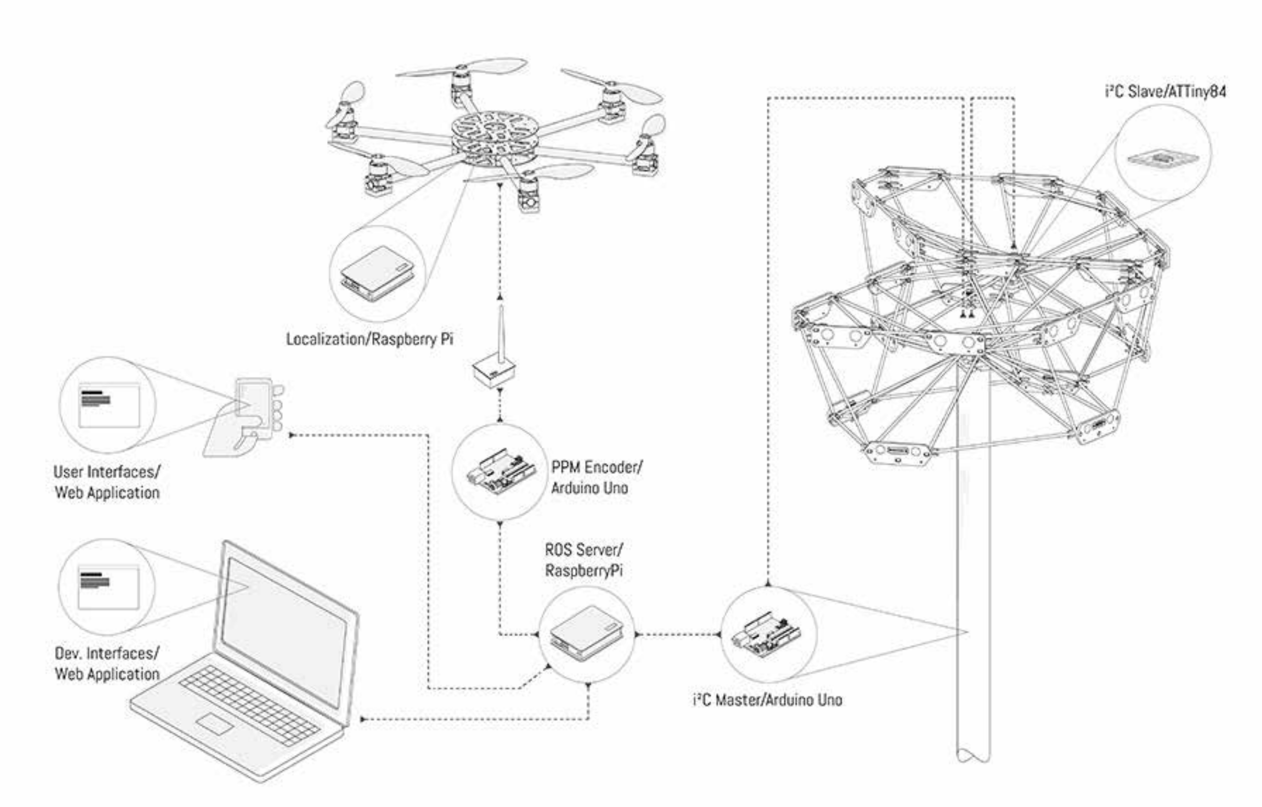
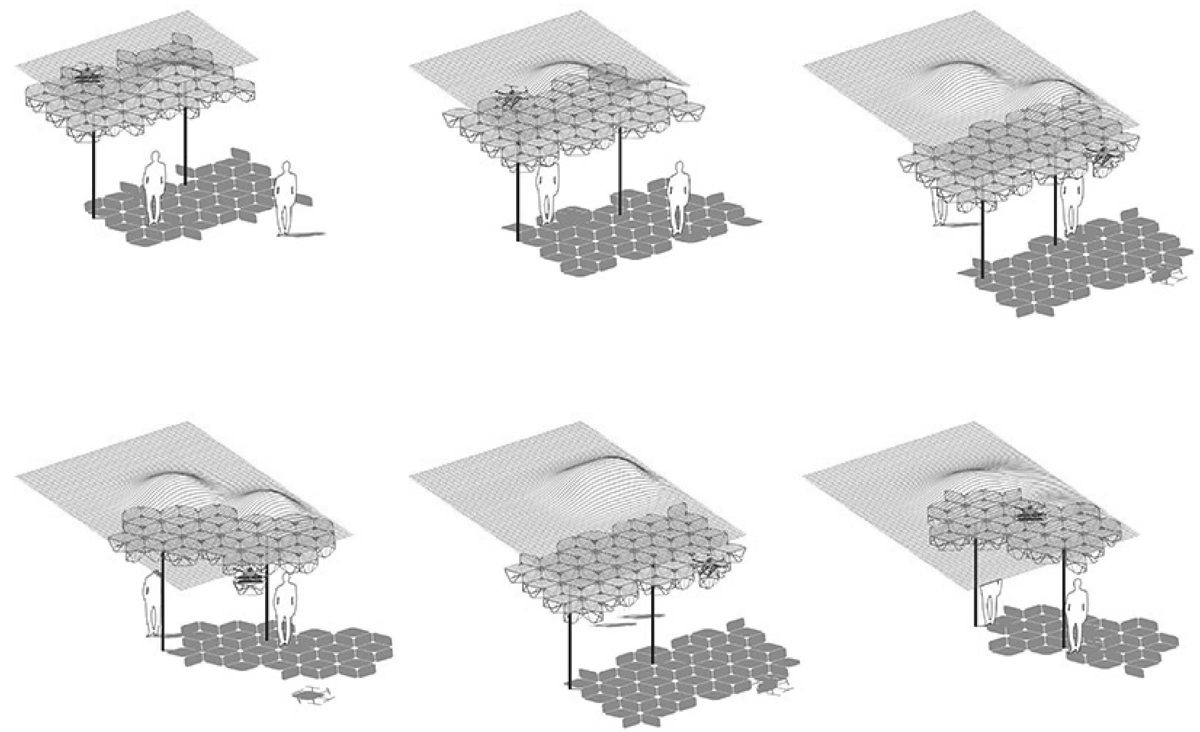




Holographic brickwork

Project data

University / research center: software developer Fologram
Project team: Fologram advancement team
Equipment: heads-up Hololens–Microsoft's augmented reality glasses
Digital tools: Fologram's App
Year: 2019

Scale:

- technological unit
- technological subsystem
- **architectural system**

Project applications:

- **exterior walls**
- roof
- **interior walls**
- interior floors
- cladding
- decoration
- scale model

Outcome advancement:

- **virtual model**
- proof of concept
- research prototype
- **built project**

Materials:

- **mono-material**
- multi-material

- low-engineered
- high engineered

- **ceramic**
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- **3D modelling**
- parametric design
- algorithmic scripting
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- **smart assembly**
- combined processes

TRL target:

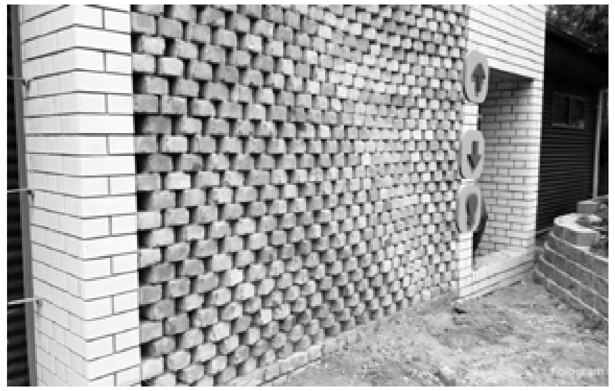
- **process innovation**
- tool (machine or end-effector)
  - visual sensing
  - tactile sensing
- design outcome

TRL advancement:

- research (1-2-3)
  - basic principles
  - concept and application formulation
  - concept validation
- **development (4-5-6)**
  - experimental pilot
  - **demonstration pilot**
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- **production process management**
- uncertainty management
- lack of a predictive model
- workcell management
- load bearing properties
- on-site installation
- **on-site assembly**
- resource consumption
- scalability
- interface of the elements produced with complex surfaces
- **level of detail of the outcome**
- development of new materials



Description

The software developer Fologram has found an experimental way to adapt AR in architecture. In 2019, a brick wall with complex geometry was built with an innovative system that reduces the construction time. The application designed by Fologram translates a 3D Rhinoceros file into instructions that are projected into the heads-up display of a Hololens AR glasses system. By wearing these lenses, construction teams can see where to put each brick to achieve a complicated structure. The cameras and positioning sensors in the Hololens indicate where to lay the first line of bricks, and then analyze the precise angles of each layer to adapt the instructions as the wall rises.

Feedback

Fologram's team is going against the trend compared to manufacturers who are currently investing in robotics. They claim that even the most sophisticated vision algorithms cannot adapt to the unpredictability of most construction sites. However, in the future it will be interesting to see whether both technologies can be integrated into an integrated workflow.

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Camera project

Project data

University / research center:
Project team:
Research program: Skanska leads a research consortium on construction robotics. The research and development program is in collaboration with UK's innovation agency, Innovate UK, and the Engineering, and Physical Sciences Research Council
Equipment: customized ABB desk robot on a mobile platform
Digital tools: customized programming
Year: 2016 - ongoing

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- **exterior walls**
- **roof**
- **interior walls**
- **interior floors**
- **cladding**
- **decoration**
- **scale model**

Outcome advancement:

- virtual model
- proof of concept
- **research prototype**
- built project

Materials:

- mono-material
- multi-material

- low-engineered
- high engineered

- ceramic
- wood
- stone
- metal
- composite materials
- plastic
- concrete
- plaster

Design process:

- 3D modelling
- parametric design
- **algorithmic scripting**
- **virtual simulation**

Fabrication process:

- additive
- subtractive
- smart assembly
- **combined processes**

TRL target:

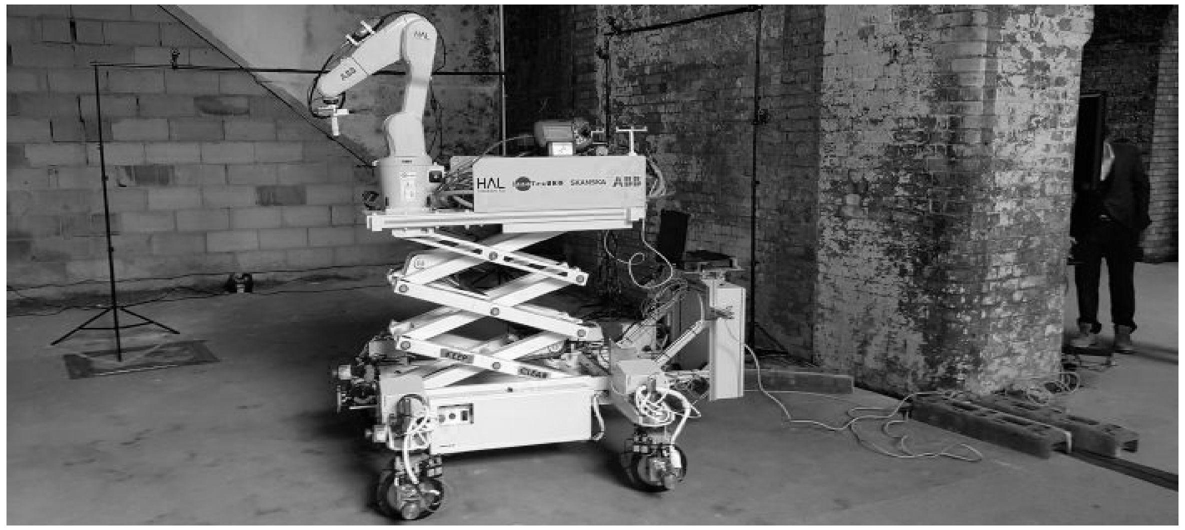
- process innovation
- **tool (machine or end-effector)**
  - **- visual sensing**
  - **- tactile sensing**
- design outcome

TRL advancement:

- **research (1-2-3)**
  - basic principles
  - **concept and application formulation**
  - concept validation
- development (4-5-6)
  - experimental pilot
  - demonstration pilot
  - industrial pilot
- deployment (7-8-9)
  - early stage implementation
  - release version
  - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- **uncertainty management**
- lack of a predictive model
- **workcell management**
- load bearing properties
- on-site installation
- **on-site assembly**
- resource consumption
- **scalability**
- **interface of the elements produced with complex surfaces**
- level of detail of the outcome
- development of new materials



Description

Skanska is taking pioneering steps in robotics. The company is leading a research consortium to study robotic applications in the construction industry. The company is exploring how robots can be used for mechanical, electrical, hydraulic and carpentry tasks to produce building components. This work would be done in situ or in temporary mobile factories that allow production under controlled conditions close to the building site. The main output of the CAMERA project is the creation of a prototype of a semi-autonomous mobile platform capable of moving around a construction site and understanding its geometry through visual sensing. This mobile platform is a proof of concept to bring robots to the construction site and automate everything that can be automated.

Feedback

Skanska's approach is linked to the fact that the current state of the art in the application of robotic technology to the construction of small units shows that while individual processes can be automated, existing systems do not offer the flexibility and reconfigurability needed to generate overall productivity improvements in a cost-effective way. From this starting point comes the need to push research towards new solutions that bring together multidisciplinary skills. Breaking down the limit of the use of robots on-site means affirming the mass customized architecture in the Fourth Industrial Revolution.

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Cobotics on-site

Project data

University / research center: Construction Robotics
Project team: Construction Robotics engineering department and advancing construction team
Equipment: Mule 135 (lb) - Material Unit Lift Enhancer. It is a "lift assist device" designed for handling and placing material on a construction site. Mule can lift up to 135 lb or 61 kg.
Digital tools: cusotmized programming software
Year: 2017 - ongoing

Scale:

- **technological unit**
- technological subsystem
- architectural system

Project applications:

- **exterior walls**
- **roof**
- **interior walls**
- interior floors
- **cladding**
- decoration
- scale model

Outcome advancement:

- virtual model
- proof of concept
- research prototype
- **built project**

Materials:

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Design process:

- 3D modelling
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Fabrication process:

- additive
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TRL target:

- **process innovation**
- **tool (machine or end-effector)**
  - **- visual sensing**
  - - tactile sensing
- design outcome

TRL advancement:

- research (1-2-3)
  - - basic principles
  - - concept and application formulation
  - - concept validation

- development (4-5-6)
  - - experimental pilot
  - - demonstration pilot
  - - industrial pilot

- **deployment (7-8-9)**
  - **- early stage implementation release version**
  - - extensive implementation

Technical complexities:

- digital process management / modeling
- production process management
- uncertainty management
- **lack of a predictive model**
- **workcell management**
- load bearing properties
- on-site installation
- on-site assembly
- resource consumption
- **scalability**
- **interface of the elements produced with complex surfaces**
- level of detail of the outcome
- development of new materials

Description

Mule is a system that helps to automate certain phases of the construction process. The hardware allows the construction units to be lifted without the effort of human workers. This system can be installed on-site and programmed using customised software that enables position sensors to be activated. Mule has been used in North America for lower-value constructions, to test the process and optimize workflows. This system has also been tested in Europe, demonstrating that for small constructions the investment is around 150,000 euros. A trained construction worker can manually handle blocks into position using the specially designed gripper designed by Mule, also created by Construction Robotics. The lifting assistance device can handle material weighing up to 61 kg, reducing fatigue and injuries among workers.

Feedback

Mule was developed by Construction Robotics in New York. The tool is the result of several iterations aimed at producing an affordable prototype that can be easily installed on-site. The concept lies in helping the workforce to carry out tiring tasks in a collaborative way, following the logic of co-botics. Early operational results have shown that the use of automated construction site systems can increase productivity from 50 to 400%. This result can be achieved without the need to replace masonry workers but, otherwise, by improving their working conditions and allowing them to focus on other aspects such as accurate positioning of construction materials. Systems like this analyzed allow to advance the construction culture by eliminating unnecessary actions and focusing on the quality of the project and process. The future of construction foresees the intensification of the design phases and the growth of digital skills also in the construction phase.

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5.2.4 Operating tools deriving from the analysis of case studies

The case study analyses highlight the flexibility of the production models that are related to fabrication-aware digital computational workflows. The projects illustrate the necessity of the designer to both expand and take responsibility of the robotic programming phases. The programming takes place through the definition of parameters that guide the information of the process, through the data-driven strategy. The computational process makes it possible to link creative and design aspects, performance evaluation, and manufacturing process parameters in a single phase. The optimization of the kinematics, a key element for the execution of each manufacturing process, also takes place through a dialogue that is established between designer and computer, with the support of the technical parts that expand the cognitive possibilities of the resulting synthesis of design and tool.

The flexibility of parametric models is one of the key potentials of the operating methodology. Parametrics allow designers to visualize and analyze a series of design options in order to identify optimal solutions that meet certain criteria. At the same time, an increase in variables is a critical factor. The greater the complexity of the data structure describing the relationships between the geometric parameters and the performance criteria conducted in the early stage phase, the greater the difficulties in monitoring and validating the resulting operational information. This assertion becomes exponentially more relevant when assuming the scalability of processes for architecture.

Among the available production processes that link design and manufacturing, additive manufacturing is the production method that potentially allows for the shortest production chain because it can build without the need for mounds or indirect processes. Furthermore, the ALM allows to create morphologically complex components without spatial limitations, avoiding the difficult assembly of the pre-fabricated parts, with a large margin of improvement as regards the level of detail of the result. There is also a sustainability component in the use of ALM that derives from the possibility of using the print material only where necessary (through the use of algorithmic computational optimization), reducing the weight of the elements and the incidence of waste materials. The additive process, given its technical and performance characteristics, is suitable both for the realization of technological units and for the construction of architecture through a seamless printing process. For these reasons this process is the most potentially compatible with the typical problems of the restoration site.

The analysis of the case studies has also shown the contemporary development of Cartesian ALM technologies (such as the D-Shape system) and of the so-called ALM large-scale robotic technologies. The Cartesian tools are mainly of the powder-based type using an X and Y gantry system and a layer based Z movement. In contrast, the robotic system works in a solid-based way and use materials such as cement, sand and clay with mechanical characteristics suitable for the realization of large structures. In applications in the construction sector, both production methods limitation is the poor performance of materials in relation to regulatory requirements. In addition, Cartesian machines for ALM require a large working space, as production must take place within the gantry system and the printing area. The advancement of the technology suggests that the additive processes on-site can be carried out more effectively through the use of end effectors installed on multi axis robots.

The analysis of the case studies set the premises for a laboratory experiment to simulate a conservative action on a relevant architecture, proposing an innovative process. This experiment will use an anthropomorphic robot customized with an end effector able to extrude cold material (cold extrusion). One of the significant aspects of ALM for applications at the architectural scale is the possibility of using multiple materials in relation to the performative parameters that differentiate each individual project. The resources available and the early stage of the project suggest the use of a low-engineered, economical, sustainable and recyclable material. The various limitations are viewed as positive considerations for the creation of a minimally viable prototype[55] to be used as a proof of concept for the overall workflow.

The key points of the experiment are therefore:

- define an experimental laboratory workflow;
- use the robotic tool to intervene on an existing architectural element that is actually damaged;
- test an element of complexity that can occur on-site using ALM large-scale robotic systems and show progress in technical knowledge in this field of research;
- design an end effector for ALM optimized to operate in complex geometric contexts;
- define a customized volume.

To address these issues, it is essential to observe on a closer scale the workflows that led to successful experiments in academic research.

55 "What Is A Minimum Viable Product, And Why Do Companies Need Them?" in *Forbes*. Available at: https://www.forbes.com/sites/quora/2018/02/27/what-is-a-minimum-viable-product-and-why-do-companies-need-them.

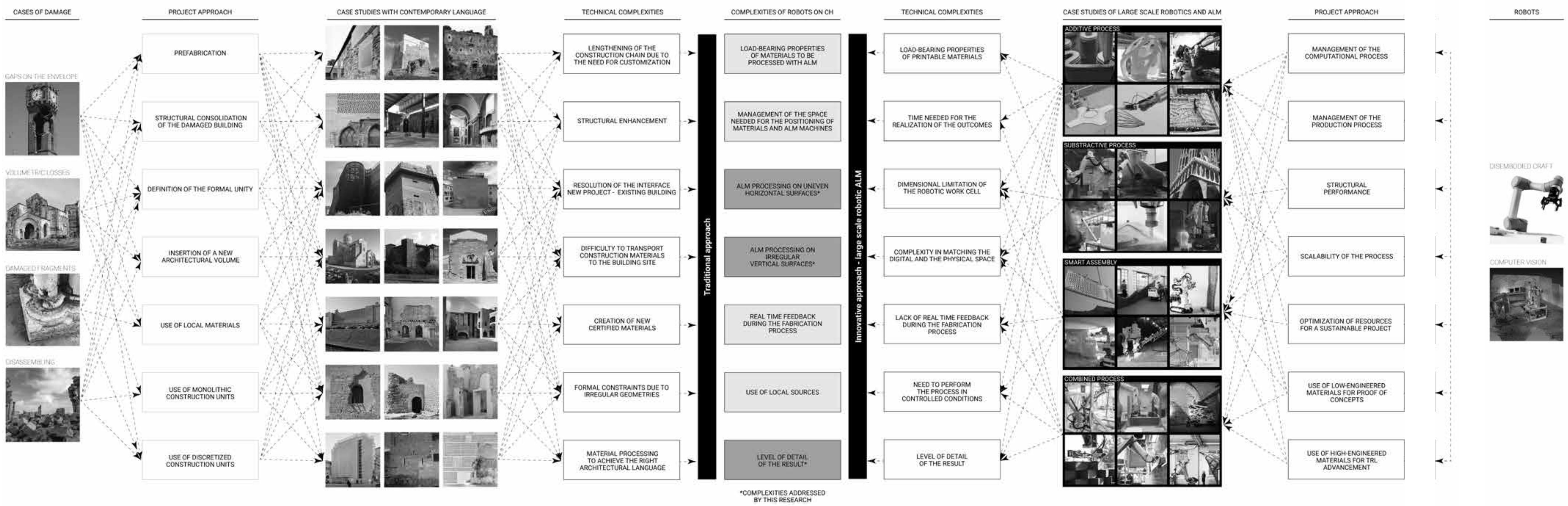

Fig. 5.2 Complexities of using robots in Cultural Heritage: 1) load-bearing properties of materials to be processed with ALM; 2) management of the space needed for the positioning of materials and ALM machines; 3) ALM processing on uneven horizontal surfaces*; 4) ALM processing on irregular vertical surfaces*; 5) real time feedback during the fabrication process; 6) use of local sources; 7) level of detail of the result*. *Complexities addressed by this research.

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PART III - BRIDGING THE GAP BETWEEN DESIGN AND PRODUCTION

6 Hypothesis of workflow: on-site robotics

ABSTRACT

This chapter is the link between analysis and applied research. All the elements studied are the premise to narrow the field of investigation towards the output of the dissertation. The deepening of state of the art and case studies led to the development of a working methodology. The methodology is a workflow, which carries the logic to perform and validate the application. The workflow is fundamental to analyze limits and potentials in the use of robo - digital fabrication for conservation and customized production through additive layer manufacturing. It was decided to structure the workflow, through diagrams, in four main stages: 1) analysis, 2) design, 3) fabrication, and 4) construction.

In the upcoming paragraphs, an operational workflow hypothesis is formulated. It is based only on theoretical knowledge. In this research context, the investigator approached the laboratory experience without prior first-hand exposure on the subject. This condition was an opportunity to deepen the topic of university education and the skills needed in preparation for the Fourth Industrial Revolution.

As mentioned, a laboratory phase followed the hypothesis. From this derives the possibility of dual reading of the workflows, vertically and horizontally. The vertical scroll explores the different phases, from analysis to construction, in a logical / chronological order. The horizontal reading, instead, allows placing alongside the hypothesis and the results achieved, to verify congruencies and inconsistencies. This approach enables comparing with the same metric: hypothesis, experiment, and future developments. The experimental results inform future developments and speculations on further applications on a broader spectrum.

Keywords: *Digital Workflows; On-site Robotics, Additive Digital Production, Architectural Products*

6.1 Narrowing the subject of research towards an applied experiment

"The workflow is intended as a digitally integrated working method, as a means to increase efficiency and explore new design potentials. They are largely driven by parametric or associative modeling [Scott Marble, 2012]

The analysis of the case studies narrowed the field of investigation toward an applicative hypothesis. The complexities encountered in the example of recovery of existing buildings are united by complexities that concern:

- the accessibility of the areas to be restored;
- the management of the work space to carry out the work;
- the geometry of pre-existing structures;
- the need to produce customized elements on a case-by-case basis.

Applied research started from a strictly theoretical basis, defined in the state of the art. The performance of the work therefore represents an opportunity to identify:

- the skills needed to innovate the construction workflows in the recovery site;
- the role of education to prepare the next operators in the sector;
- the development opportunities of a complex sector such as the construction sector.

In order to carry out the laboratory research, a hypothetical workflow was developed to analyze the identified phases for limits and potentials in the use of digital fabrication for conservation (Fig. 6.1). The workflow, elaborated diagrammatically, served to explain the project intentions to the research team of the College of Architecture and Design at LTU. The hypothetical workflow was a starting point for formulating the evaluation of results, based on the comparison with what was supported only by theoretical knowledge.

Design control tools are increasingly required throughout the design and construction phases to help manage the complexity of technological component's relationships to architectural work adjacent to pre-existing systems. New scenarios are offered by the synergy between digitalization of the building process (BIM-HBIM) and new paradigms of production of architectural artifacts and building components (robotic production techniques). In this operating context, the traditional concept of three-dimensional representation is transforming. The digital model is no longer solely a physical representation but also a simulation carried out by software designed to study behavior in certain situations. The digital model becomes a critical product of a creative-interpretative act, a knowledge contribution for the building. This process enriches the designer's experience, up to "providing us more experience than we could have gathered, without the mediation of the imaginable, in an empirical relationship with reality" (Maldonado, 1992). The building construction model becomes itself a subject in the direct digital transfer of material production on the construction site.

The long held concept of standardization is being overridden by off-site production and a greater openness to experimentation with innovative aggregation systems capable of enhancing performative parameters. By shortening the site's supply chain, the need to produce components in an industrialized way loses some of its significance. The advantages offered by on-site production make it possible to go beyond the site's supply logic and the consumption of resources. At the same time, the cogency remains to be able to guarantee quality and performance standards capable of raising the average quality of new buildings, optimizing the use of human resources. The re-proposal of certification systems in this scenario also responds to the request to solve the gap between the performance of the individual components and their installation. The operational dynamics of additive manufacturing have the potential of precision, flexibility, site safety, full control of construction times, and measurable costs and performances.[1] This allows access to industrialization levels even in the recovery process, without losing sight of the uniqueness of the historical asset.

Taking into account not only the site-specific but also the project-specific factors that characterize the interventions on the existing condition led to the creation of a hypothesis of an ALM workflow on the Cultural Heritage. This workflow allows for highlighting highly unique designs combined with complex project conditions. The concept of workflow is here taken back to the meaning expressed by Scott Marble in the book *Digital Workflows in Architecture: Design – Assembly – Industry.* A (digital) workflow is a procedure that "leverage the potential of digital tools to link existing sectors of the industry in new sectors in response to the growing demand for intelligent processes" (Marble, 2012). For the purposes of this research, the workflow is configured as a pilot case, "a design methodology in digital form" (Burger, 2012) repeatable so the robots can operate in the survey, diagnostics and (where considered compatible) production of components. Worksite operations can be temporary (made safe) or permanent in response to building degradation over time, emergency, or post-first emergency conditions.

1 Advantages and disadvantages of automation: https://www.britannica.com/technology/automation/Advantages-and-disadvantages-of-automation.

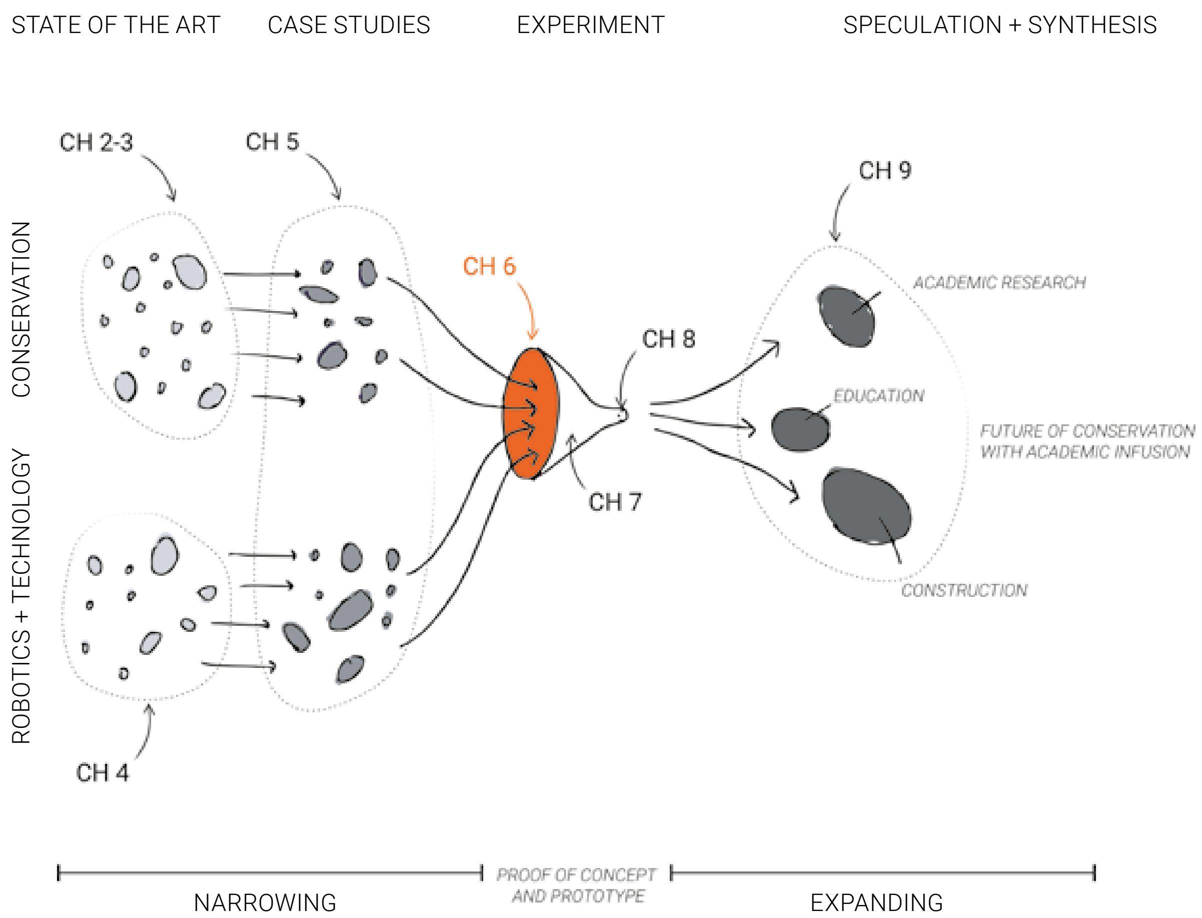


Fig. 6.1 Development of the methodology in the chapters of the dissertation (CH 1-9). Chapter 6 is the link between analysis and applied research.

6.2 The fragmentation of the traditional building process

The laboratory experiment was an opportunity to evaluate how new technologies (3D scanners, drones, lidar sensors) and production tools (robots, 3D printers) affect traditional building construction, especially for the realization of non-standard elements. The experiment allowed for a translation from a "static vision of the project, already a heritage of the pre-industrial era, to a dynamic vision of design, which needs a new logic of relationship with the operations and procedural instruments" (Spadolini, 1981). The traditional building process consists of a sequence of complex operations performed to transform a system (Argiolas et al., 2013) understood as "the organizing or bringing together of a set of inputs or resource flows, and their assembly or transformation into a specified building output or product, in a given period of time, on a specified site" (Groak , 2002). In other words, traditional construction (Fig. 6.2) can be considered as an organized sequence of decision-making phases (Briggs, 1925), operational and management, which involves an investment of limited resources and productive factors to obtain a "superior unity for each phase of transformation" (Ossola and Jona , 1999).

The decision-making phases have a large impact on the organization of work, as: "you cannot have 40 people show up on-site and figure out the material at the end. We need processes, logistics. We need to know how to arrive at a certain amount of time".[2] As Pierluigi Spadolini recalls in the text *Designing in the Building Process*, the production sequentiality originates with the artisan production, where "the designer's knowledge was related to that of the [highly specialized] manufacturer with a direct control of resources and technologies to provision " (Spadolini, 1981). Craft production can be described as "a sequence of discrete steps, with a clear threshold marking the termination of each step and the commencement of the next. In metallurgy these thresholds are precisely where the key operations take place". Every operation happens after the previous one completed (Zaffagnini, 1981). The metalsmith, as an example, has periodically returned his iron to the fire (Ingold, 2013).

The technological influence in production processes varies in historical periods according to the production tools used. The connection between design and construction has weakened with the advent of industrialization, which has delocalized production and simplified the technological elements for their repetitive production. Industrialization "has determined a flattening of the artisan interpretation" and has brought constraints to the design determined by the downstream production technologies (Spadolini, 1981). This has inevitably led to restrictions in the work of the architect, forced to limit formal and constructive choices based on industrial production. It also distilled the professional role of the contemporary architect. The designer now must assume the availability of off-the-shelf components (Groak, 2002). Off-site serial prefabrication was a widespread construction practice for social housing in Europe in the 1950's and 1960's. Closed prefabrication is characterized by the strong rigidity of mass production, for which it is possible to reproduce constructive components in a serial and cost-effective manner while eliminating the inaccuracies of craftsmanship. It is based on a limited use of materials, the use of efficient but at the same time, standardizing productive systems, limited / de-skilled labor, and to many the perception of detrimental architectural quality.

2 Information from CritPrax kick-off lecture at LTU-CoAD by Karl Daubmann. Fall semester 2019.

In the 1980's, in a period of strong technical experimentation in Italy, Spadolini systematized building construction dividing the production of the technological units into three categories:

- industrial, for which the products are made with the same invariable characteristics;
- semi-industrial, whereby products can be made with different characteristics within the limits of technology and assembly methods;
- craft, so the products are made on-site based on the manual labor capacity and within the material limits. The artisanal construction means that the designer is a central figure for the development of all phases.

In these years architects worked with open, more flexible, and resilient prefabrication systems. This approach allowed for variations in production, allowing designers to work with greater design freedom on materials and components such as sub-systems (elements of the envelope or roof) that made up the macro-systems. The designer assumed the availability of special variations. This approach constituted the productive context within which the first theorization on mass-customization was hypothesized, defined for the first time in 1987 with the publication *Future Perfect* by Stanley Davis. In this way the idea of a production process was introduced through which to produce differentiated elements with the same economic efficiency with which the standardized ones are produced (Davis, 1997). This theory was based on the ongoing trends with the Third Industrial Revolution, defined by the computerization of production processes and the democratization of machines (Pine and Davis, 1993). The 1980's, at the threshold of the Digital Turn, allowed designers to visualize a socio-cultural transition between hand-making, mechanical making, and digital making. The theme of digital making has opened to philosophy, with the Theory of Objectile by Bernard Cache (Cache, 1998) and the theme of multiple variations (Deleuze, 1993) introduced by Deleuze. The theme of digital making is seen as a possibility to generate calculus based forms, creating variations that can be produced using digital manufacturing technologies through the language of the algorithm (Carpo, 2017).

Despite the potential soon defined by the spread of digitalization in the architectural field, mass production (customization of products and production processes) was received with greater difficulty than in other sectors. As per tradition, every building can still be considered a prototype (David, 1989), "an almost experimental product that responds to the creative ability of the architect and the workers" (Spadolini, 1981), with little opportunity for learning between one project and another. Every architectural realization is the result of a "temporary coalition of people and organizations", probably working together for the first time (Groák, 1994). We still construct in the same way as Gothic cathedrals were erected, with the only difference being that the tools are more sophisticated [and materials have less longevity, ndr], but with the same philosophy: "manual control, human operator visual feedback, and big positioning error" (Balaguer , 2000). Returning to the definition of a building drafted by the Italian architect Duccio Turin, conventional buildings are characterized by "uniqueness":

every building is a unique project on a unique site. Each building project has therefore to be organized distinctly (Bon, 1991). This aspect is even more evident when talking about conservation, as the layer of cultural and identity uniqueness of historic buildings must be added.

The use of digital fabrication is an opportunity to innovate the construction sector and architecture by promoting a method based on the customization of the form to be ideally operated on-site, operating like the ancient master-builders. Today there are numerous limitations (such as, for example, safety measures in the workplace, according to the relevant legislation) which make it difficult to scale-up this approach from the FabLab environment to the construction site. However, current trends lead to the conclusion that in the near future it will be necessary to be prepared to face a rapid change in the construction sector, as a result of the Fourth Industrial Revolution. In short, these trends are:

- the spread of CAD / CAM tools globally;
- the increasing investments in digitization;
- democratization in the purchase and use of robots;
- the simplification of digital interfaces for algorithmic design and translation in robo-scripting;
- global diffusion of the skills;
- the definition of new high-engineered materials, compatible with 3D printing or robotic production;
- the need, in the construction sector, to operate more on built heritage in the next few decades;
- the need, particularly in Europe, to pass on to the future a significant Architectural Heritage.

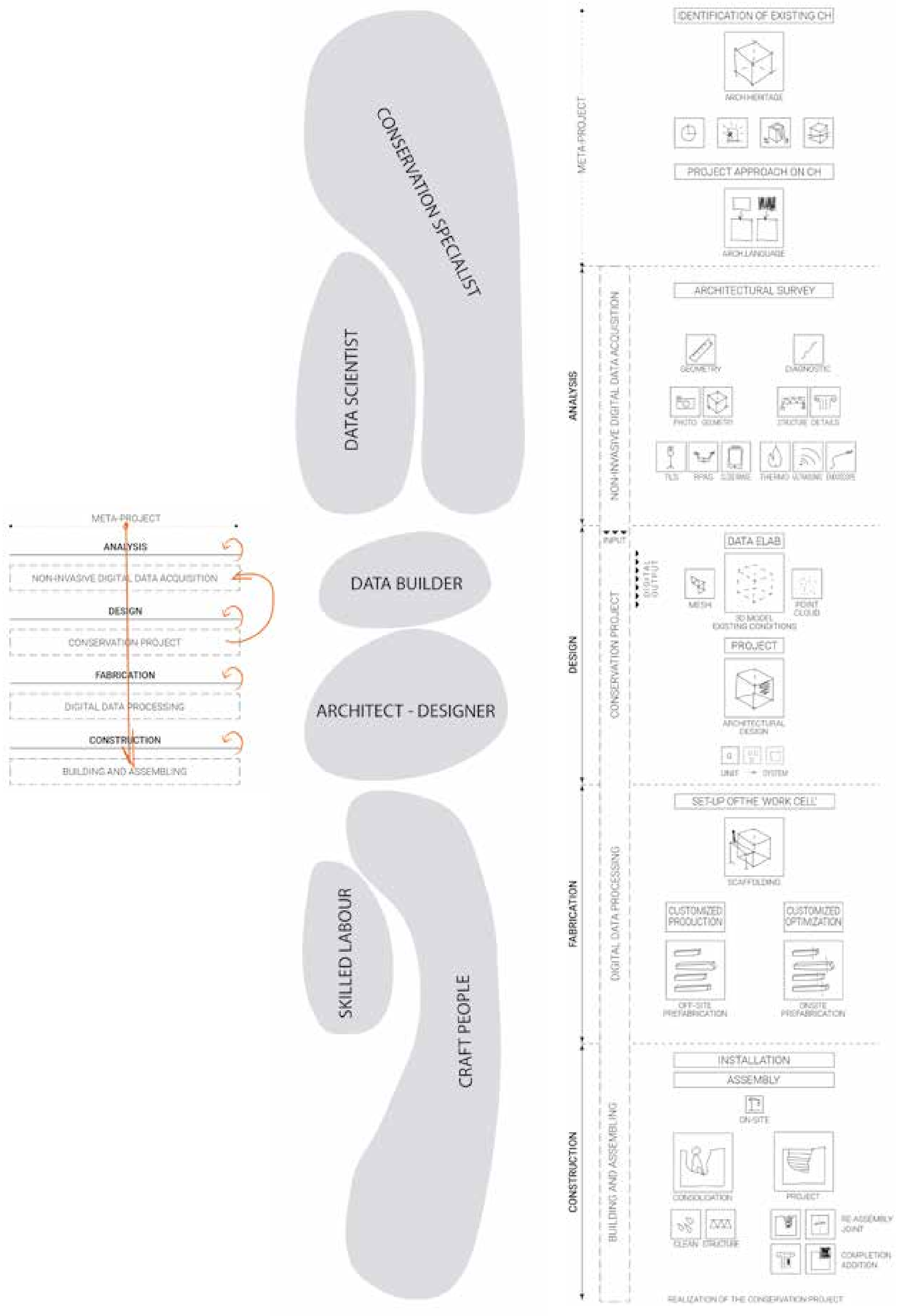
This research formulated a hypothetical workflow, to be validated through an experiment that aimed to make the traditional construction process more fluid, supported by the integration of parametric data and technologies that allowed iterative-predictive operation. At the time of narrowing the research it was decided to use as main tools:

- **robots;**
- **additive manufacturing;**
- **digital fabrication for the customization of production.**

These tools are based on a digital fabrication-aware computational process (Deuss, 2015) and serve for the phases of survey and recovery of damaged parts of historic buildings.

Fig. 6.2 Right: diagram of the traditional building process workflow, divided into metaproject, 1) analysis 2) design, 3) fabrication, and 4) construction phase.

TRADITIONAL BUILDING PROCESS: SKILLS, PROCESS, AND RELATION BETWEEN THE PHASES



6.3 Phases of the hypothetical workflow to innovate building processes for conservation

The workflow was formulated with four phases:
1. analysis
2. design
3. fabrication
4. construction

The phases anticipated the meta-project, which is necessary to address the operating methodology (Fig. 6.3).

0) Meta-project

Scale of the intervention

Resuming the definitions proposed by Mario Zaffagnini in *Designing in the Building Process*, the first step was to understand the operational sequences carried out in the recovery site and to define the scale of the intervention:
- technological unit;
- architectural sub-system;
- architectural system.

At different scales, historic buildings may be subject to degradation due to various causes:
- degradation over time;
- emergency conditions;
- post-emergency situations;
- Iinaccessible sites for social, political, or environmental reasons.

On the basis of the extent of the damage, the design approach can be defined in order to achieve the figurative unity of the building, in terms of architectural image, mainly identified in the dichotomy:
- linguistic continuity;
- linguistic discontinuity.

1) Analysis

Positioning of robots on-site

Analysis of an operational control unit allows for the structured movement of robots on the building site. The references for this type of system are:
- the robocrane systems hypothesized in 2004 at the University of Southern California in Los Angeles (Khoshnevis, 2004);
- the mobile unit defined for the construction of the Pike Loop[3] in Manhattan in 2009;
- the robotic construction platform developed at MIT (Keating et al., 2014);
- research work on building site automation, still in progress, conducted by the BIM4placement project;[4]
- research on driverless construction vehicles carried out by the CAT company.[5]

This system must meet the following characteristics in order to enable new modes of in-situ construction:
- fast set up time;
- accurate positioning on a ground reference point;
- extended physical reach;
- high load capacity;
- possibility to perform complex functional movements;
- control of oscillations;
- possibility of operating at different heights;
- flexibility and capability of implementing different operations and large-scale digital fabrication (additive-subtractive-assembly);
- accuracy of the end-effector;
- real time control through sensors to create a feedback loop;
- computer vision (2.5D robots).

Dimensional survey

Execution of a non-invasive survey to obtain a database of digital information to be shared globally on platforms for archiving architectural heritage. The survey obtains the most precise digital model possible, without direct designer contact. It can be conducted through the following techniques:
- TLS (Terrestrial Laser Scanning) and close range survey using robots;
- RPAS (Remotely Piloted Aircraft Systems) using drones.

Robots can be customized by end-effector defined by devices such as:
- cameras;
- laser distance measurers;
- laser scanners.

Diagnostics

Execution of a non destructive analysis (White, 2017). Robots can be used for use with pre-programmed:
- toolpaths thermographic cameras;
- ultrasonic devices;
- endoscopes.

Visual sensing

Robot sensors are devices that detect information about the root and its surroundings, and transmits it to the robot's controller. Analog sensors produces signals such as force, pressure, temperature, humidity, speed, acceleration, and vibration. The operation can be organized as follows:
- image acquisition;
- image digitization: dividing an image into a matrix of discrete picture elements (pixels), which is a value that is proportional to the intensity of the scene. The intensity value for each pixel is converted into its equivalent digital value by an analog-to-digital converter;
- image processing: the image is measured, and the measurements are digitized;
- image dimensional analysis;
- image interpretation: recognizing the object (object recognition). The robot identifies an object by comparing it to predefined models, through machine learning.

2) Design

Digital Design

The underlying theme of the whole process is the digital management of the design and the use of the same design tools to instruct the various downstream tools involved. Therefore, the design tools belong to the BIM systems, which for the existing become HBIM.

The adoption of these information-representative tools allow for project work phases to be carried out in a transparent way.

Project phases extend to the whole building process, putting in relation elements of composition, technological, and structural with construction phases (BIM 4D), cost estimation (BIM 5D), certification (BIM 6D) and life cycle

3 Pike Loop in Manhattan by Gramazio and Kohler research: http://gramaziokohler.arch.ethz.ch/web/e/projekte/159.html.
4 BIM4placement: http://www.bim4placement.eu/.
5 CAT:https://www.cat.com/en_US/articles/customer-stories/built-for-it/thefutureis-now-driverless.html.

management (BIM 7D + CAFM).[6] It thus becomes possible to carry out much more aware and thorough reasoning on the sustainability of the work. The definition of the design procedure and the programming of the tools involved (machine control) takes place through:

- generative design;
- parametric design.

According to these modalities a number of design decisions are transferred into a dynamic computational model within an associative geometry environment. The management of control sliders that meet the needs of project and input parameters allows for increasing design iterations to explore geometric variations and optimization aligned to the post-scientific approach to design.

3) Fabrication

Customization of production

The operational flexibility of robots as generic machines made them able to perform tasks based on input data. To carry out a customized process the use of off-the-shelf end-effectors was assumed for the performance of various on-site operations of:

- survey / geometric data collection
- diagnostics / collection of qualitative data
- additive or subtractive production, depending on the defined design approach.

6 BIM dimensions in construction: https://www.lead-innovation.com/english-blog/building-information-modeling.

4) Construction

Consolidation / Stabilization

The flexibility of the robot can allow the execution of light actions to consolidate unstable artefacts through non-invasive interventions with robotic precision even in dangerous contexts. To give an example, the creation of a reticular cage on-site in a very short time to consolidate a part of unsafe construction. This can be done while waiting for subsequent interventions and avoiding further collapses following the temporal advancement of the instability (seismic, infiltrations, sagging). This could be done with a 3D printer with a raised mechanical arm and a fast setting and rapid hardening resin. Obviously the problem of the oscillations in height of the mechanical arm or of the computerized self-regulation of the position of the nozzles will have to be solved. Robots can perform:

- air or surface cleaning operations;
- surface consolidating treatments;
- injections of consolidating resins;
- integrations of fillings, holes, chipped edges or insertion of pins through mechanical nailing;
- securing areas subject to collapse and in particular undercut geometrical configurations by cutting or installing customized construction elements.

It is also possible to think of longer lasting consolidation solutions like the need to eliminate structural damage for safety. Robots could be used to deposit material from the outside after macro-washing or blowing air to eliminate the presence of dust and increase the adhesion of the deposited material to the masonry. Or again, with the same technology, it is possible to hypothesize rebuilding the configuration of a ruined vault so that there are no gaps between the segments. With the extrusion deposit technology it is also possible to produce entire portions of the building, but overturning the parts so as to allow the formation of sections with horizontal cavities in the floors.

Additive Digital Production

Additive layer manufacturing (ALM) is hypothesized for the production of components and with this there are different types of machinery suitable for large-scale production. The laboratory experiments carried out at a global level confirm the extrusion of bulk materials (cold extrusion or 3D plotting as the most promising method)[7] using extruders installed on robots. In this case the procedure provides:

- identification of the most suitable material for the new insertion, ideally selected from a certified mixtures database. It is hypothesized that the main characteristics are rapid drying and rapid hardening, to reach a sufficient load bearing capacity to support the following extrusions; in the case of structures carried as a cornice the characteristics of lightness can also be increased through, for example, alveolar masses, with materials different from the original;
- definition of the most suitable production methodology, if production directly on the damaged architectural component or if prefabrication and installation on-site;
- if the project needs require a temporary intervention (for example, safety in post-first emergency to avoid further collapses) it is possible to take as reference the cellular fabrication (C-Fab) processes developed by the Branch Technology[8] company or the space AM anti-gravity project being developed at the IAAC with the Mataerial[9] project;
- if instead the design address is permanent, definition of the interface between building and new construction, with possible punctual / linear connections to merge the existing building to the reconstructed component.
- on-site definition of a digital fabricated 3D printed reversible matrix to create the architectural system by managing: materials, component density, weight, and production time.

The powder-bed deposition systems on the cartesian work area are more complex to install on-site (their bulk is made up of an external offset with respect to the structure to be printed), they do not have a high level of detail (LOD), and the printing times are longer.

The integration between the computerized survey, processing of the collected data, and direct dialogue with the production machines provides a convincing prerogative to manage the existing digital data in a new way. This digital workflow blends concept and fabrication; digital objects are embedded with properties and rules through relationship to other objects. Taking the words of Mario Carpo in the essay “The Digital, ‘Mouvance’, and the End of History”, the integration of processes can have a double

7 In the programming language, 3D plotting differs from the commercially defined "3D printing". In the first case the machine is guided by the toolpath, in the second case the information is supplied by a matrix.

8 Branch Technology: https://www.branch.technology/process.

9 Mataerial project at IAAC: http://www.mataerial.com/. See also: https://vimeo.com/55657102.

reading: “the vertical integration of computer-based design and manufacturing is creating new forms of digital artisanship, narrowing the Albertian divides between the designer and the producer.[10] The digitally enhanced horizontal integration of actors who may be called to intervene in the design process (Carpo, 2010). A particularly relevant aspect is the possibility of extending the sensory / cognitive capacity of the robot through sensors and a designer-machine-material feedback loop communication process. This makes it possible to work with a non-linear and adaptable dynamic system: "the topic you were talking about, automatic feedback, digital craftsmanship” (Carpo, 2014).

Intervention in emergency conditions suggests wide margins for applied research on materials and the refinement of application dynamics. It should also be emphasized that often the gaps to be filled are no longer exactly the same as they were geometrically before the earthquake or instability: a bit of stone recovered after a collapse may no longer be sufficient to restore the carrying capacity of a ruined arch and probably will require the creation of a new piece with a slightly different shape. In the case of degraded voids or elements to be replaced of the architectural system scanning will be required. Scanned geometry leads to reproduction of new inserts and taking care to preserve, in the new inserts, the same stiffnesses (nature of the material and geometric properties). In terms of planning, further reflections must be developed in relation to the expressive languages and the technical characteristics to be adopted, with respect to the pre-existence. This is a crucial point in the restoration process of the building. The graft represents in any case an alteration of the original palimpsest (morphological and structural) which can be rendered more or less in analogy with the existing one. In this sense, the constantly evolving versatility and flexibility of ALM technologies can operate within the spectrum of replacement or expressiveness.

10 The paper is published in the journal: *GAM, Architecture magazine*. Mario Carpo continues the argumentation: " the partici- patory nature of the design process that digital horizontal integration may now support and promote is equally evocative of the collective and often anonymous way of building that was common on medieval building sites before the Humanists' revolution". In this dissertation the concepts of vertical and horizontal integration are analyzed in the optimal skills needed to carry out the workflows.

HYPOTHESIS OF DIGITAL WORKFLOW

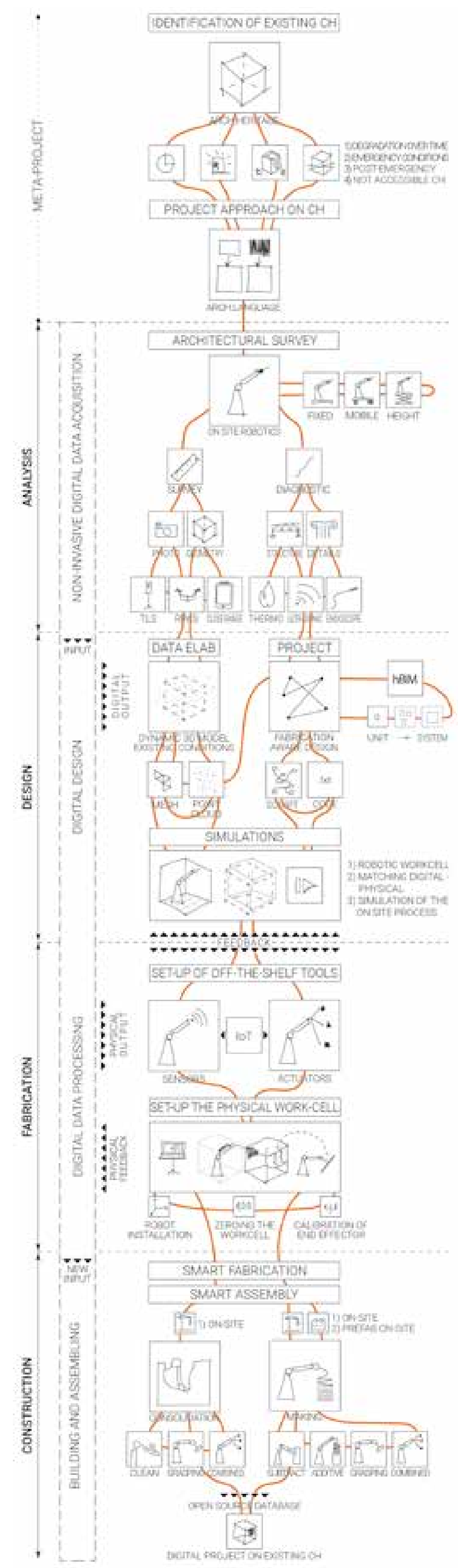


Fig. 6.3 Right: hypothesis of digital workflow to innovate innovate the building process for conservation. It was elaborated upstram the applied phase of this research.

6.4 Fields of application, prerogatives and materials

The aforementioned processes contribute to defining innovative procedures in order to fill, for example, masonry gaps following damage and destruction caused by natural disasters and conflicts. This gap filling refers to the possibility of intervening on the continuity of the envelope (vertical curtain walls and masonry vaults), with a view to reversibility, with micro-interlocking interventions, or with integrations of larger parts. This gap filling can (1) put in safety post-earthquake the precarious structural systems, (2) repair the tears of the enclosure that open to the penetration of the bad weather, or (3) add elements (or entire structural support meshes) for the future reuse of the building.

Responses can range from a single component to an entire wall, up to the extreme of inserting new functional volumes in the existing ancient envelope. These implementation methods can be identified in the use of a robot on-site that replaces the person in dangerous areas of intervention and processing (the 4D tasks that are dangerous, dull, dirty, or dumb).[11] This can also be done by setting up a temporary structure on the sidelines to house printing machinery to print under controlled conditions of temperature, humidity, and air speed. These factors can have a negative impact, for example, on the processing-setting-hardening cycle of the printing mixture, on the density of the material obtained and consequently on the performance of the final result. For a more complex first stage of set-up, a substantial speed of reconstruction would result in emergency situations, especially considering a rapid "centralized" prototyping unit at the level of settlement or minimum intervention unit that acts as a reference for several construction sites. It is therefore possible from the digital survey to be able to produce components that coincide with the voids to be filled or the non-recoverable parts to be replaced, calculating exact geometrical tolerances and morphologies for insertion and fixing on the edges.

Material compatible with historic buildings will need to be used (both for structural and non-structural interventions), such as for example mixtures of raw earth, stone or brick (to have reconstructed materials similar to the original, but sufficiently shapeable and homogeneous), conglomerates based on cement or hydraulic lime and wood pulp. As well as hoops, ligatures, tie-rods, reinforced seams, additional linear members are often used for the consolidation / stabilization of heritage buildings. In order to construct profiles and scaffolding for structural support for masonry or wooden floors, plastic polymers (in association with the drafting of carbon fibers) could be the basic material to produce components with physical characteristics similar to metal. Especially after destruction from disaster, the use of recycling existing materials can be useful through the grinding of specific collapsed parts. Some positive aspects of the use of detritus collected in a differentiated way from damaged buildings can be found, for example, in the possibility of limiting the impact and transport costs (which often suffer from the limitations and critical issues of the access roads to the emergency areas) of materials not available directly on-site.

11 Robot 4Ds tasks: https://www.forbes.com/sites/bernardmarr/2017/10/16/the-4-ds-of-robotization-dull-dirty-dangerous-and-dear/.

6.5 Choice of the right architectural language

To decide the material with which to operate and the tools with which to generate and apply material, it is essential to establish the linguistic / expressive result that one wants to achieve in the context of a conservative recovery process. One must understand whether it is preferable to reconstruct the missing parts in imitation of the originals (with aggregates, binders and additives that favor the non-recognition of the reconstructed piece, if not at close observation). Or in contrast, it may be appropriate to vary the components, resolution and texture of the external surfaces in such a way as to leave the new entry fully legible (by a formal counterpoint or by morphological analogy which excludes complete mimesis, but integrates equally with the pre-existence). The end-effector used for a specific process can itself be a characteristic image tool. The trace of the toolpaths with its upstream design can become a necessary identifier of a precise design language, so that the architectural object designed "bear the scars of the technique by which it was made" (Ingold, 2013). If allowed to represent the digital process "it can not only imitate and automate manual processes but also the digital processing machine. The culture of craft in concert with digital tools. Translating manual processes into a digital craft means rethinking the traditional processes and adapting to the characteristic features of the machine " (Bonwetsch et al., 2010).

The tooling marks can create a readability that can create parallels, or three-dimensional levels that are not coplanar, with the pictorial integration techniques that go from the completion with the "rigatino" technique. It is also possible to enter more specifically the detail to be reconstructed, up to the abstraction or chromatic selection, operating with macro-spots of uniform tonality. In both cases, the options for mixing and depositing both with recycled material (the "secondary raw materials") and with new raw materials remain valid. Such distinctive reasoning can be done both in the case of conservative additions, and for design additions to the envelope. It is the latter case of insertions that do not want to be confused with the volumes of the pre-existence, implementing an expressive duality through the strong differentiation of forms that, through additive production, can favor free curved geometries managed at a computational level.

In this context, it is useful to take up the concept of algorithmic design (Tedeschi, 2014) which goes beyond parametric design by opening up advanced and still unexplored scenarios of shape management. From the informative data as a computable design parameter inserted in a controlled and predefined digital environment, a designer can embed the logics with which the variables of the project can become matter. Although today speaking of parametric design seems to be synonymous with Building Information Modeling, the desire to transpose the relationships between different parameters into form emerged already in the 1960s thanks to the studies of Luigi Moretti (Mulazzani and Bucci, 2002) or materialized in by Sergio Musmeci (Nicoletti, 1999). The exploration of these forms, achieved without the help of a computer, can be considered the presupposition for today's algorithmic design, in which, given the input design variables, the focus is on the design of the algorithm capable of correctly responding to the project requirements, considering that parameter changes are an immediate time-saver. In this way new perspectives and new design scenarios can be defined, where "design intelligence is rooted in design methodology" (Burger, 2012).

6.6 Technology Readiness Level: a scale to evaluate applied research

The workflow was formulated for validation on a laboratory scale. In order to objectively evaluate the results, the Technology Readiness Level (TRL) was used because it is a shared analysis scale in European design and clearly defines the state of technological progress. The TRL is defined as follows:[12]

TRL 1 – basic principles observed;
TRL 2 – technology concept formulated;
TRL 3 – experimental proof of concept;
TRL 4 – technology validated in lab;
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies);
TRL 6 – technology demonstrated in a relevant environment (industrially relevant environment in the case of key enabling technologies);
TRL 7 – system prototype demonstration in an operational environment;
TRL 8 – system complete and qualified;
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space).

Given the recent spread of additive manufacturing technologies to the architectural scale (Lim et al., 2012), and even more specifically to existing volumes, it is necessary to acknowledge the fact that this research represents an attempt to promote debate and experimentation in this area. The results are not expected to be directly applicable as a planning tool in the decision making phases or in the executive elaboration of technological details. What is promoted instead is an attempt to advance the state of the art of knowledge so that other academic research centers interested in the same themes can make use of them and understand the applicability to broader areas of research. To prepare these construction systems for an insertion in the construction sector it is necessary that the level of technological maturity is such that it can be effectively competitive in the market. For this reason, we recall the concept previously expressed by the Technology Readiness Level (TRL) adopted by NASA (Mankins, 1995) in the 1990's and taken up as a reference code also at the level of European research.

Still taking into consideration a scale of values from 1 to 9 (Straub, 2015), we can state that the basic principles (TRL1) have already been observed with regard to the attempt to combine digitalization and industrialization through customized manufacturing. The first significant steps have been taken in the field of design objects and an interest has already emerged towards extending the intervention scale to architecture. Furthermore, the design push towards architecture's complex shapes, in particular if carried out experimentally through additive manufacturing that allows the use of the material only where needed, suggests the possibility of interfacing with complex geometries derived from pre-existing architectural systems. Speculative ideas (TRL2) on the use of digital fabrication have also already been formulated to define approaches to the recovery of culturally relevant architectures.

Examples are the work of the research group led by Mark Burry for the digitally controlled construction of the columns to continue the construction of Gaudì's Sagrada Familia in Barcelona (Sheil, 2012), or the Digital Gothic laboratory experimentation conducted at MIT for the realization robotics of a mass-customizable formwork, inspired by forms and methods of craftsmanship deriving from the Gothic tradition (Clifford et al., 2014). At the moment, digital approaches to heritage have materialized through an advanced study based on parametric rules of design geometries and the use of subtractive systems, "reductive manufacturing", for the actual manufacture, in continuity with nature of materials that were historically cut, carved, sculpted, and chiseled. What is still lacking in this area of research is a focus on additive production systems and the contribution they can make outside the scale of the study model, the decorative detail or even the experimental mock-up. This experiment then takes the form of a proof of concept (TRL3) structured to define the operational premises for subsequent laboratory studies (TRL4). More rigorous technical studies can finally bring the technologies examined to be proven and demonstrated in a relevant environment such as the industrial one (TRL5-6) through the elaboration of explanatory prototypes (TRL7) to reach the final certification (TRL8) and the placing on the market as a competitive element (TRL9).

The transition between TRL3 and TRL4 requires dissemination. The international *Fabricate 2011*[13] conference (Glynn and Sheil, 2011) was the first to recognize digital fabrication in the construction industry. The diffusion of the academic work carried out up to that point was then followed by the two-year events *Rob|Arch 2014-2016-2018*,[14] for which each speculative laboratory work was a step towards the advancement of the Technology Readiness Level in additive robotics manufacturing, subtractive, kinematic and combined movement.

12 Technology Readiness Level within Horizon 2020. The definitions come from NASA. See: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf.

13 Fabricate conference: http://www.fabricate.org/.
14 Rob|Arch: https://www.robarch2020.org/.

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PART IV - TECHNICAL LAB EXPERIMENT

7 Evaluation of applicability of the research

ABSTRACT

This chapter describes the applied research carried out as the output of the dissertation. This experiment was an opportunity to observe and critically analyze the limits imposed by the technical tools and multidisciplinary skills.

Given the recent spread of additive manufacturing technologies to the architectural scale, and even more specifically to existing volumes, it is necessary to acknowledge the fact that this research represents an attempt to promote debate and experimentation in this area. The results are not expected to be directly applicable as a planning tool in the decision making phases or in the executive elaboration of technological details.

What is promoted instead is an attempt to advance the state of the art of knowledge so that other academic research centers interested in the same themes can make use of them and understand the applicability to broader areas of research. To prepare these construction systems for an insertion in the construction sector it is necessary that the level of technological maturity is such that it can be effectively competitive in the market.

The research experiment was intended as a feasibility check for an in-situ simulation of a restoration operation using additive robotic manufacturing on a damaged, geometrically complex element of a relevant architectural building element. The simulation was structured to allow iterations in a laboratory environment on a 1: 1 scale prototype of a wall portion scanned with digital survey systems.

As a proof of concept the various constraints were understood as complementary specific objectives. In this instance, the available tools, the limited budget, the skills of the research assistants involved in defining the work flow, all informed the potential of the upstream objectives. Rather than carry out this work in an industrial / production space, the experimental nature of the work required a flexible prototyping environment. This work took place in the LTU - CoAD buildLab. The experiment is structured in ten phases. The DIY tool making stage is particularly highlighted. At the end, the final outcome is presented.

Keywords: *Applied Research, Experimentation, Large-Scale Robotic Additive Layer Manufacturing*

7.1 Additive manufacturing and digital heritage in a build-lab environment

"Making creates knowledge, builds environments and transforms lives [Tim Ingold, 2013]

The key points to set the experimental contribution[1] of this research were focused on digitization and digital transformation efforts in Cultural Heritage conservation as led by European and international institutions. As a means of critically defining both technical and cultural aspects for the state of the art in conservation and existing heritage, an in-person laboratory experience was undertaken. The laboratory experience took place between the second and third doctoral year. It served to both highlight the potential and limits of current digital fabrication technologies in relation to existing architectural approaches at an architectural scale. The laboratory experience was viewed as an application test-bed for material production through the design, fabrication, and application of a specially designed additive manufacturing robotic tool. This custom robotic tool deposited material based on extrusion paths programmed through a mediating interface between existing geometry and tool definition.

There are several theoretical scenarios that can be opened based on the premise of a laboratory experiment. The transformation of the digital data on the subject is allowed to go beyond the digitalization of the design processes to more deeply investigate aspects of customized production. The creation of components, in this case, were integrated with geometry extrapolated from a building of high value witnesses. This work opens up the possibility of defining a workflow that unites concept and fabrication. This workflow deploys automated tools to intervene on a damaged architectural element and then replaces the tangible heritage with the digital one according to UNESCO definitions. Secondly, this concept test is an opportunity to deepen the human-tool interaction in the digital recovery site, emphasizing the skills that the architect must have to respond to the constant updating of technologies to support the activity.

1 A summary of the chapter of the dissertation "Evaluation of applicability: additive manufacturing and digital heritage in a build-lab environment" was double blind peer-reviewed and published in the international journal *Cubic*, edited by the Hong Kong Polytechnic University. The single-author paper "Additive manufacturing. The technologies of layers interventions and the Cultural Heritage of the built environment" describes the research topic affiliated with the Ferrara University and Lawrence Technological University (CoAD). The paper was accepted for the issue 3_ Design Making: The Values Had, The Object Made, The Values Had. For further information see: https://www.cubicjournal.org/wp/issue-3-design-making/.

The experimentation took place thanks to a collaboration established between the Department of Architecture of the University of Ferrara and the Lawrence Technological University in Southfield, Michigan (USA), in the academic year (fall semester and spring semester) 2018/2019. In particular, the College of Architecture and Design provided a workspace at their buildLab and makeLab facilities.

7.2 Motivations of the experimental testing

Currently automation technologies for architecture are mainly in the phase of analysis and experimentation in the field of academic research. There is still no shared and standardized global system for the use of robotic systems and additive manufacturing in architectural practice. Since these technologies are still developing for the architectural production sector, there has already been a transfer of knowledge and skills from the research context to the profession. There are still many unresolved aspects in terms of technology advancement and widespread knowledge. There are no definitive solutions that give effective proof of an economic and procedural advantage in the use of robotic instruments for the design or the protection of the existing. What can be hypothesized, however, is a tendency in the research sector to achieve certain objectives, or the possibility of using the potential of industrial machines of different derivation at different scales of intervention (Zaffagnini, 1981) such as:

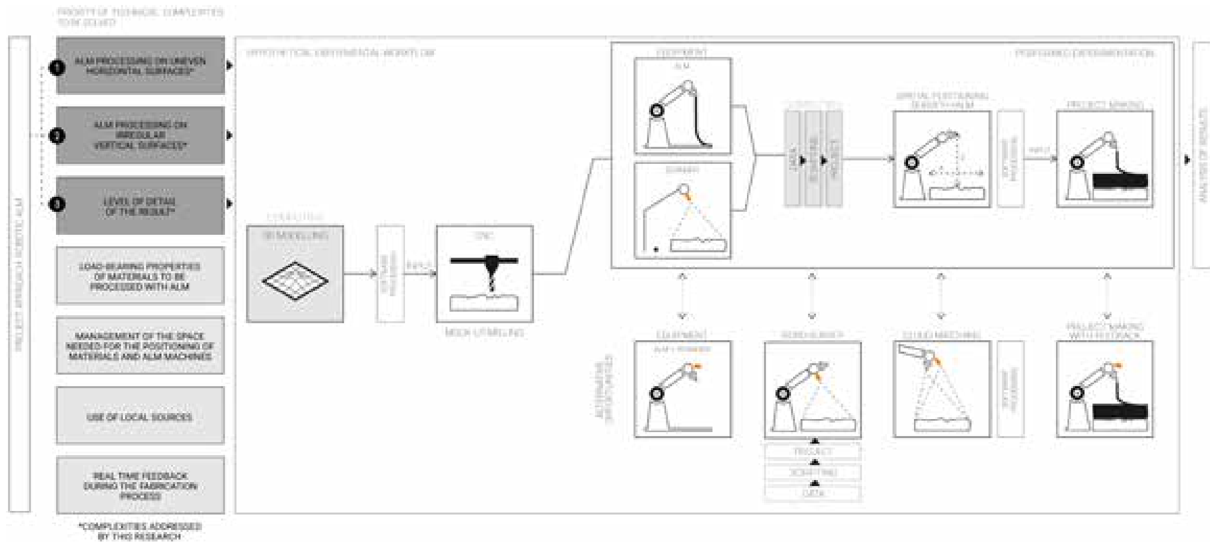
- technological units, the basic units that make up a building;
- technological subsystems, which derive from the aggregation of base-units;
- architectural systems, which are complex organizations of technological systems interrelated.[2]

The technical aspects to be solved in relation to unit - subsystem - system (UNI 8290 - classification of technological units), are in turn related to the advancement of technical knowledge regarding computational processes, material engineering, implementation of components, the resolution of technical aspects in the phases of construction, and the scalability of the process.

This experiment (Fig. 7.1) was an opportunity to observe and critically analyze the limits imposed by the technical tools and multidisciplinary skills, regarding:

- digital computational process management;
- production process management through additive manufacturing;
- design and production through digital fabrication and additive manufacturing of the suitable tools to customize the operation of the industrial robot, taking into consideration the necessary tools and the timing of realization;

2 The distinction between technological units, technological subsystems, and architectural systems where theorized in Italy between the seventies and the eighties by the architect and professor Mario Zaffagnini. His theoretical speculation was published in the book *Progettare nel Processo Edilizio.* He explains the design methods in relation to production of elements and construction phases. In the seventies, Italian companies were experimenting a technical shift in the construction industry. The aim was to encourage prefabrication to make housing more affordable by forcing the standardization of the architectural language.



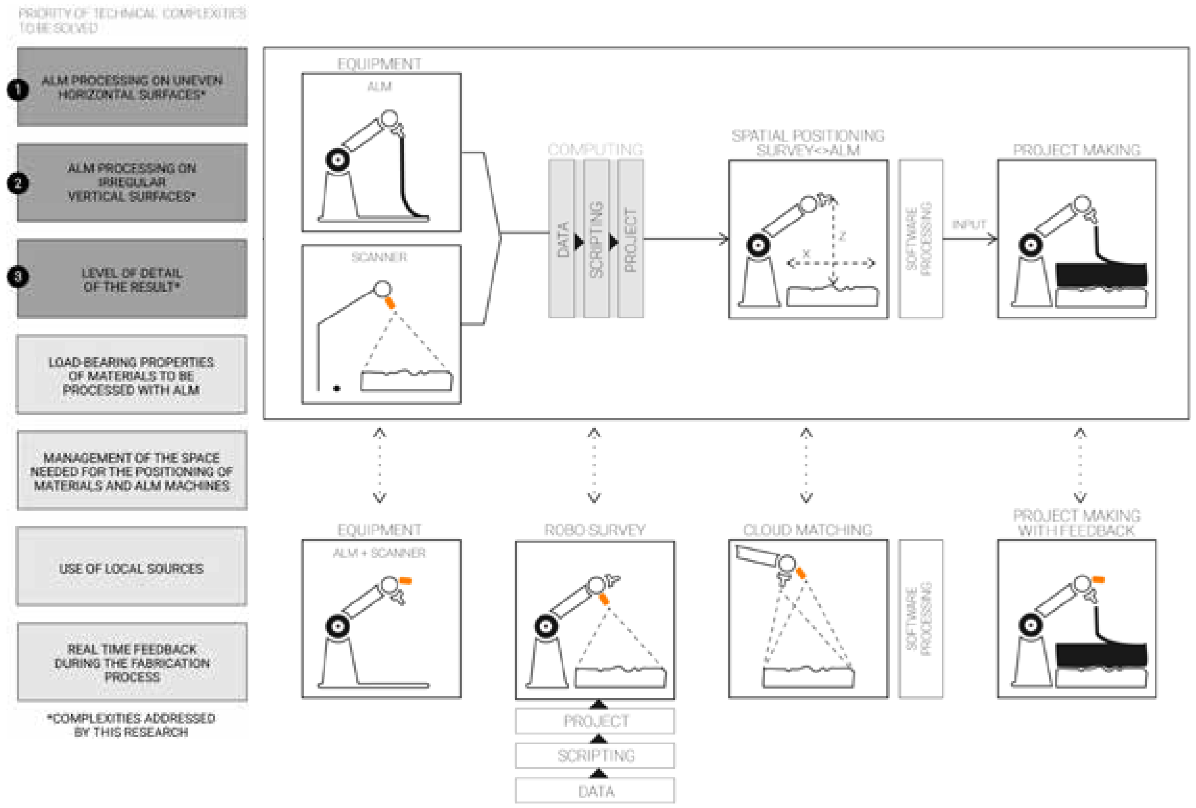


Fig. 7.1 The motivation of the experiment is to explore technical complexities in the automated building-site. The aim is to operate on existing irregular surfaces to test robotic additive manufacturing.

- the physical behavior of the materials chosen for this concept test;
- the management of dimensional tolerances in the transition between the digital and physical model;
- the scalability of additive manufacturing processes.

In relation to computational processes, for example, a current limit is the need to have integrated skills on the part of operators in the sector, in order to manage the entire design process. The simultaneous management of the formal generation and digital manufacturing process implies a level of management complexity with which few designers have already faced in the professional sphere, as they are used to operating according to traditional construction logics. The production phase in fact implies the possession of knowledge with respect to the production methods made available by the use of generic tools such as industrial robots (organization of the work area, setting of tools to perform a particular function, management of tolerances to ensure correspondence between physical environment and digital space) and the ability to design and calibrate specific end-effectors that guarantee the customization of elements and processes.

From the point of view of materials, especially with regards to additive manufacturing, there is still the need to optimize physical and mechanical properties to be adopted in construction. An aspect related to scalability, is represented by the fact that the realization of units and technological systems is closely linked to the size and range of the degrees of movement that the tools offer. The management of tolerances deserves a separate reasoning, as for this experiment the interaction of a robotic arm with a real pre-existing context, defined by irregular surfaces both on the vertical and horizontal plane, is expected. The work area for this experiment was enriched with elements of complexity, compared to a generically regular geometry provided by a laboratory workcell.

Given the recent spread of additive manufacturing technologies to the architectural scale (Lim et al., 2012), and even more specifically to existing volumes, it is necessary to acknowledge the fact that this research represents an attempt to promote debate and experimentation in this area. The results are not expected to be directly applicable as a planning tool in the decision making phases or in the executive elaboration of technological details. What is promoted instead is an attempt to advance the state of the art of knowledge so that other academic research centers interested in the same themes can make use of them and understand the applicability to broader areas of research. To prepare these construction systems for an insertion in the construction sector it is necessary that the level of technological maturity is such that it can be effectively competitive in the market.

For this reason, we recall the concept previously expressed by the Technology Readiness Level (TRL) adopted by NASA (Mankins, 1995) in the nineties and taken up as a reference code also at the level of European research. At the moment, digital approaches to heritage have materialized through an advanced study based on parametric rules of design geometries and the use of subtractive systems, "reductive manufacturing", for the actual manufacture, in continuity with nature of materials that were historically cut, carved, sculpted and chiseled. What is still lacking in this area of research is a focus

on additive production systems and the contribution they can make outside the scale of the study model, the decorative detail or even the experimental mock-up. This experiment then takes the form of a proof of concept[3] (TRL3) structured to define the operational premises for subsequent laboratory studies (TRL4). More rigorous technical studies can finally bring the technologies examined to be proven and demonstrated in a relevant environment such as the industrial one (TRL5-6) through the elaboration of explanatory prototypes (TRL7) to reach the final certification (TRL8) and the placing on the market as a competitive element (TRL9).

The transition between TRL3 and TRL4 requires dissemination. The international *Fabricate 2011* conference (Glynn and Sheil, 2011) which was the first to recognize digital fabrication in the construction industry. The diffusion of the academic work carried out up to that point was then followed by the two-year events *Rob|Arch 2014-2016-2018*, for which each speculative laboratory work was a step towards the advancement of the Technology Readiness Level in additive robotics manufacturing, subtractive, kinematic and combined movement.

3 3 The notion of TRLs started in the 1960s, with its codification in a 1969 report describing a needed "technology readiness review". In the 1970s, the need for a "technology-independent scale" was identified and this was referred to as "technology readiness levels" in the late 1970s. The TRL scale gained widespread use in the 1990s as part of the development of the "Integrated Technology Plan for the Civil Space Program". The TRL scale was also used for numerous NASA documents throughout the early 1990s. In 1995, it was created the "Technology readiness levels" white paper that provided a "compressive set of definitions of the technology readiness levels" which serve as the basis for the TRL system to this day and the system gained popularity internationally as well. There are nine technology readiness levels. TRL 1 is the lowest and TRL 9 is the highest: https://www.nasa.gov/directorates/heo/scan/engineering/technology/txt_accordion1.html. The scientific community is in search of the TRL10. Where a topic description refers to a TRL, the scale definitions apply, within Horizon 2020 work programme 2014-2015: https://ec.europa.eu/research/participants/data/ref/h2020/wp/2014_2015/annexes/h2020-wp1415-annex-g-trl_en.pdf

7.3 Objectives

The research experiment was intended as a feasibility check for an in-situ simulation of a restoration operation using additive robotic manufacturing on a damaged, geometrically complex element of a relevant architectural building element. The simulation was structured to allow iterations in a laboratory environment on a 1: 1 scale prototype of a wall portion scanned with digital survey systems.

The entire process was developed, under the supervision of professors Karl Daubmann[4] and James Stevens, through the support of grad students with different skills in the field of digital fabrication:

- Nathan Ickes,[5] grad student of CoAD (LTU), makeLab research assistant with a cultural background in architecture;
- Zahra Almajidi,[6] grad student of Cranbrook Educational Community and buildLab specialist at CoAD (LTU), with a background in metalsmithing;
- Janelle Schmidt,[7] grad student at Yale University, alumna of LTU, and research fellow at Ballard Robotics, with a background in architecture and experience in digital fabrication.

As a proof of concept to move this work from TRL3 to TRL4 the various constraints were understood as complementary specific objectives that any work must confront. In this instance, the available tools, the limited budget, the skills of the research assistants involved in defining the workflow, all informed the potential of the upstream objective of encouraging the passing of the TRL.

7.3.1 Primary objective

- Carry out an additive robotic manufacturing workflow[8] on a pre-existing complex geometry to simulate an in situ restoration process as a prototype of workflow.

7.3.2 Secondary objective - technical evaluations

- Create a digital twin (virtual element to be disseminated) through an appropriate level of detail of the digital scans in all phases of the project;
- Simulate and build a robotic workcell that works within the geometric constraints of an existing volume;
- Program the kinematics of the robot so that it operates on the object of intervention without collisions and evaluate the dimensional tolerances that exist between virtual and physical space;
- Build an end-effector to customize the behavior of the generic robotic machine, consisting of a container and a nozzle to extrude the print material along the programmed toolpath;
- Carry out a large-scale additive manufacturing process, using a robotic arm on a damaged architectural element with geometry defined by undercuts;
- Evaluate the behavior of the extruded material from the end-effector in relation to irregular horizontal and vertical surfaces;
- Verify the physical behavior of the low-engineered printing material, also in relation to the speed of the kinematic axes of the robot, for the construction simulation in order to allow iterations and optimizations of the operating phases;
- Define the timing necessary for the manufacturing process;
- Monitor the responsiveness of the tools and any technical measures to be implemented during the different phases of the workflow, to optimize the timing of implementation.

7.3.3 Secondary objective - skills assessments

- Verify the availability of information necessary for the hardware setup and the computational programming of the robot, as there is not yet a widespread and structured knowledge at the level of university education;
- Evaluate the cognitive abilities and gaps of researchers with a cultural background in architecture and expertise in digital fabrication to create an end-effector based on open source digital resources that transforms the robot into an additive manufacturing tool.

7.3.4 Secondary objective - discussion on the experimental outcome for restoration

- Control the compositional language of the experimental output, as an architectural image of the restoration intervention;
- Define the optimal level of detail of the extruded layers for the intervention on the built element;
- Evaluate the color of the result;
- Evaluate the level of human-machine interaction in the production phases of the process.

4 Karl Daubmann profile: https://www.daub-lab.com/.

5 Nathan Ickes profile: https://nidesign.weebly.com/.

6 Zahra Almajidi profile: https://www.ltu.edu/architecture_and_design/faculty/profile.asp?_c=1479. For further information see: https://www.instagram.com/z.almajid.i/.

7 Janelle Schmidt's work at makeLab: http://make-lab.org/author/janelle-schmidt/.

8 Based on Scott Marble's definition, a workflow is intended as a digitally integrated working method, as a means to increase efficiency and explore new design potentials. They are largely driven by parametric or associative modelling, where efficiency is more of a by-product than a goal. With this approach, structure, material, and production methods become the foundation of creative-thinking.

7.4 Equipment

Rather than carry out this work in an industrial / production space, the experimental nature of the work required a flexible prototyping environment. This work took place in the LTU CoAD buildLab with implementation of tools designed, built, and used in the LTU makeLab.

Tools

- Kuka Kr6 - six-axis arc,[9] installed in a fixed location and bolted to the buildLab floor (it was not possible to operate the robot outside the range defined by the length of the arms). This was a generic industrial machine previously used in the automotive production chain and then displaced of due to periodic updates to the tools used in assembly lines. The robot will be customized to operate as a large-scale 3D printer;
- 3D printer with delta[10] type structure built with DIY purpose in makeLab, with compressed air extruder, for the additive manufacturing of clay models within a 30x30x50 cm printing area, whose kinematics was managed with Arduino system.[11] This tool was used to test the material to be used for robotic extrusion;
- Cartesian 3D printer[12] with PLA filament (thermoplastic polyester) with filament coil of diameter 1.75 mm and printing area 30x30x30 cm. This tool was used for the realization of the end-effector components.

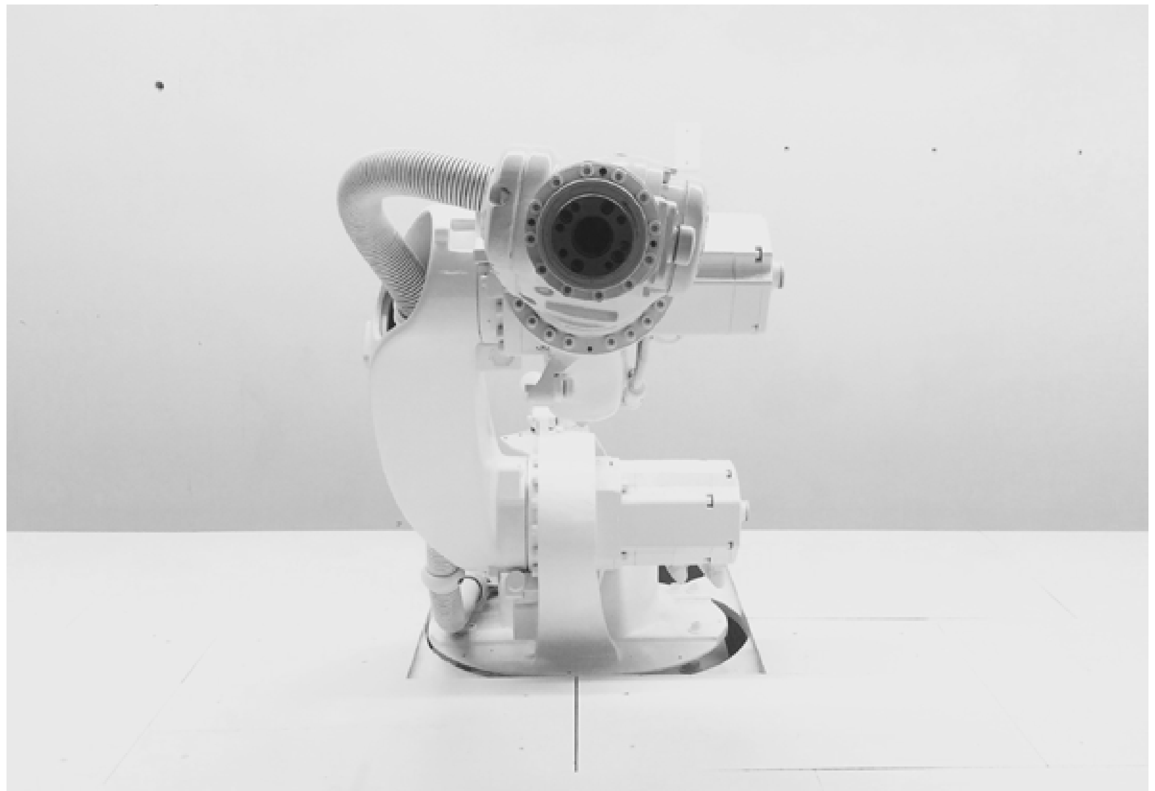
Tools to be implemented to customize the mechanical arm

- end-effector (nozzle) installed on the robot head;
- tank containing the printing material;
- extrusion system for transferring material from the tank to the nozzle.

Software to support the various experimental phases

- Rhinoceros for the definition of three-dimensional digital models;
- Kuka | Prc,[13] for the parameterization of digital models and for robotic programming;
- Repetier,[14] for the programming of 3D printers;
- Ida-Arduino executed scripts 3D printer.

9 Kuka Kr6 - arc: https://www.kuka.com/en-de/products/robot-systems/industrial-robots/kr-6, produced by Kuka as arc welders.
10 makeLab DIY delta 3D printer: http://make-lab.org/machines/.
11 Arduino: https://www.arduino.cc/.
12 makeLab DIY delta 3D printer: http://make-lab.org/machines/.
13 Kuka|Prc: https://www.robotsinarchitecture.org/kuka-prc.
14 Repetier: https://www.repetier.com/.



General features

Axes	6
Payload	6.00kg
H-Reach	1611.00mm
Repeatability	±0.1000mm
Robot Mass	235.00kg
Structure	Articulated
Mounting	Floor

Operation modes

T1 - manual
T2 - auto full speed mode
AUTO - auto low speed mode

Kinematics

LIN - Linear move: velocity (v) =k
PTP - Point to Point move: velocity (v) optimized

Robot Motion Speed

A1	156 °/s (2.72 rad/s)
A2	156 °/s (2.72 rad/s)
A3	156 °/s (2.72 rad/s)
A4	343 °/s (5.99 rad/s)
A5	365 °/s (6.37 rad/s)
A6	662 °/s (11.55 rad/s)

Robot Motion Range

A1	±114°
A2	+35° - 155°
A3	+154° - 130°
A4	±350°
A5	±130°
A6	±350°

Fig. 7.2 The Kuka robot used at the build Lab of the LTU - CoAD for the experiment: a 6 - axis Kuka kr6 - arc.

7.5 Phases of the experiment

"Architecture is an art and is essentially a reasoned state of capacity to make" [Aristotle]

The analysis of the state of the art in international research and the direct comparison with experts in the field of robotic programming and tool making informed a structured workflow consistent with the tools and resources available to meet the design requirements defined in the introduction (Marble, 2012). This flow of experimental actions, as previously expressed, served to spread knowledge about a possible approach to the themes of robotic additive manufacturing for restoration. The experiment addressed technical problems in order to push the Technology Readiness Level to a subsequent step.

The experimental phases, unpacked in the following paragraphs, required an academic year of work and were structured as listed below:

1. identified a design test-bed, that was a significant architecture in a state of damage, formulated a hypothesis of intervention supported by a critical approach to the topic;
2. performed a qualitative photographic survey of the building, selected a specific case of damage, on which it was believed that a geometric reconfiguration intervention supported by the use of a robotic tool could be compatible;
3. performed a quantitative survey of the building, compared the digital data obtained through a fast method that gave as output a mesh and those obtained from the elaboration of a point cloud, both texturized;
4. elaborated the survey data to define a digital model of the damaged architectural element being studied. Made the 3D parametric model, made editing operations more flexible and reversible. Converted the 3D model to be processed by different tools for both subtractive and additive digital fabrication;
5. selected the significant portions of the 3D model, always keeping the 1:1 study scale, so that the total space was within the limits of the robot's work cell. Prepared the digital model according to the format necessary to be materialized in the physical world; set up the experiment, created the prototype of the damaged architectural element;
6. performed feasibility checks regarding: a) the limits of the robotic instrument; b) the limits of the material as a function of the volume to be produced through additive manufacturing in order to direct the correct design of the extruder and the end-effector for the robot;
7. tool making (in this thesis described in 4 tests), ie design of the extruder and end-effector in order to customize the robot and customize the use of a generic machine for large-scale robotic additive manufacturing;
8. robo-scripting: a) generation of toolpaths; b) conversion of toolpaths to a robot code; c) digital simulation of the robot code;
9. set to zero the wall mockup;
10. definition of the project outcome (three-dimensional volume created by additive robotic manufacturing within the geometrical limits of a pre-existence) and spin off the digital / virtual asset for use in other outcomes.

Phase 1: Individuation of the test-bed, the Woodward Avenue Presbyterian Church in Detroit

The experimental phase of the dissertation was carried out at Lawrence Technological University in the USA. In order to broaden the dialogue at an international level, it was decided to share the European approach on the Cultural Heritage with researchers of the host institution. The shared goal was to address the use of additive digital fabrication in conservation, as an opportunity to update the processes of conservation of Cultural Heritage. In this field, digital tools are rarely used in the implementation phases due to the lack of studies that assess their applicability and actual benefit. The experimental phase identified a local test-bed, officially described as:

- an architectural asset under degradation or abandonment;
- a historical building classified as a national landmark, based on the federal regulation on the conservation of Cultural Heritage.

Researchers at CoAD, led by Aaron Jones,[15] are currently mapping historical architecture in the Detroit area that are under degradation,[16] resulting from the collapse of the local economic system in the 70s. Most of these buildings are included in the *Federal National Register of Historic Places* (NRHP).[17] The survey activity led to the definition of a dataset used to classify architecture of cultural relevance partially or entirely damaged, starting from those that are already labelled as a heritage[18] to be preserved. This cataloguing process has been used to find a consistent test-bed. It is an abandoned building characterised by several critical geometrical conditions to be replicated and analysed using digital tools. It was decided to examine the Woodward Avenue Presbyterian Church,[19] a neo-gothic building designed by architect Sidney Badgley and built in 1911 (Fig. 7.3). It is a national landmark[20] since 1982. The last religious service in 2005 marked the beginning of its abandonment.[21] By 2009 it had been bought by the Cathedral of Praise Baptist Church with hopes of returning it to its former architectural image. Unforeseen costs for restoration put the proposal of intervention on hold.

15 Aaron Jones, assistant professor at Lawrence Technological University and funder of AJ/A: https://www.jonesaaron.com/.
16 The negligence on Detroit built heritage takes its origin from the oil crisis that affected the United States from 1973 to 1979.
17 *Federal National Register of Historic Places* (NRHP): https://catalog.archives.gov/.
18 The dissemination of the dataset is available online at: http://www.webmodel.space/.
19 The Woodward Avenue Presbyterian Church was mentioned in two articles of 1958 and 1976, published in the *Detroit Times*: "Fiftieth Anniversary, Woodward Avenue Presbyterian Church, 1908-1959" (1958); "Heritage of Faith: Detroit's Religious Communities (1976).
20 The documentation about the Woodward Avenue Presbyterian Church in the *Federal National Register of Historic Places* is available at: https://catalog.archives.gov/id/25338557. The NRHP reference is #82002916.
21 The church appears in national databases of abandoned public buildings in Michigan, such as *Desert Places*: http://desertedplaces.blogspot.com/2013/07/detroit-city-in-decay.html. Among the abandoned places listed the church represents a landmark of urban decay: http://desertedplaces.blogspot.com/2015/09/the-woodward-avenue-presbyterian-church.html. The building was featured on Desert Places too in 2018, as representative example under the category "churches". The online post included a wide variety of photo documentation: https://abandonedplaygrounds.com/2018/11/18/abandoned-presbyterian-church-of-woodward-avenue/.

The Woodward Avenue Presbyterian Church is trimmed in limestone with a surface of rough rock with a large carved-stone entrance facade. The stained glass is ornamental tracery (Fig. 7.7). There are more ornamental stained glass windows that are full height, on the sides. A two-story wing makes up the backside of the church. Its "most distinguishing feature is a tall octagonal lantern that rises from the center of the roof that is flanked by twin, low towers that frame the church's gabled entrance"[22] (Fig. 7.4, Fig. 7.6). The interior consists of vaulted structures defined by a wooden skeleton and resting on masonry counter walls (Fig. 7.5). The irregular layout and the size and the type of bricks make it clear that the bracing and internal facings have not been designed to be left exposed. Although it is known that the last use of the church took place in 2005, the official photographic documentation for archival purposes is updated only to 1980. In 1980 the building was found in excellent maintenance conditions. In the reports, available in the following pages (Fig. 7.8, Fig. 7.9, Fig. 7.10, Fig. 7.11, Fig. 7.12), no internal or external degradation situation is reported. Currently the church shows signs of structural and envelope deterioration.

NRHP 82002916: Woodward Avenue Presbyterian Church in Detroit

The National Register of Historic Places and National Historic Landmarks includes:

- Nomination Form with the item description, location, category, use, and information about maintenance conditions;
- Nomination Form for the inscription of the building in the thematic group of Religious Structures of Woodward Avenue;
- historic photographs of the building's interior spaces and exterior envelope, updated at 1980, before its abandonment;
- topographic map of the location site, updated at 1968.

Fig. 7.3 The Woodward Avenue Presbytarian Church in Detroit. It was abandones at the beginning of the twentieth century.

22 See: https://www.clickondetroit.com/features/2017/07/11/go-inside-historic-detroit-church-built-in-1911/.

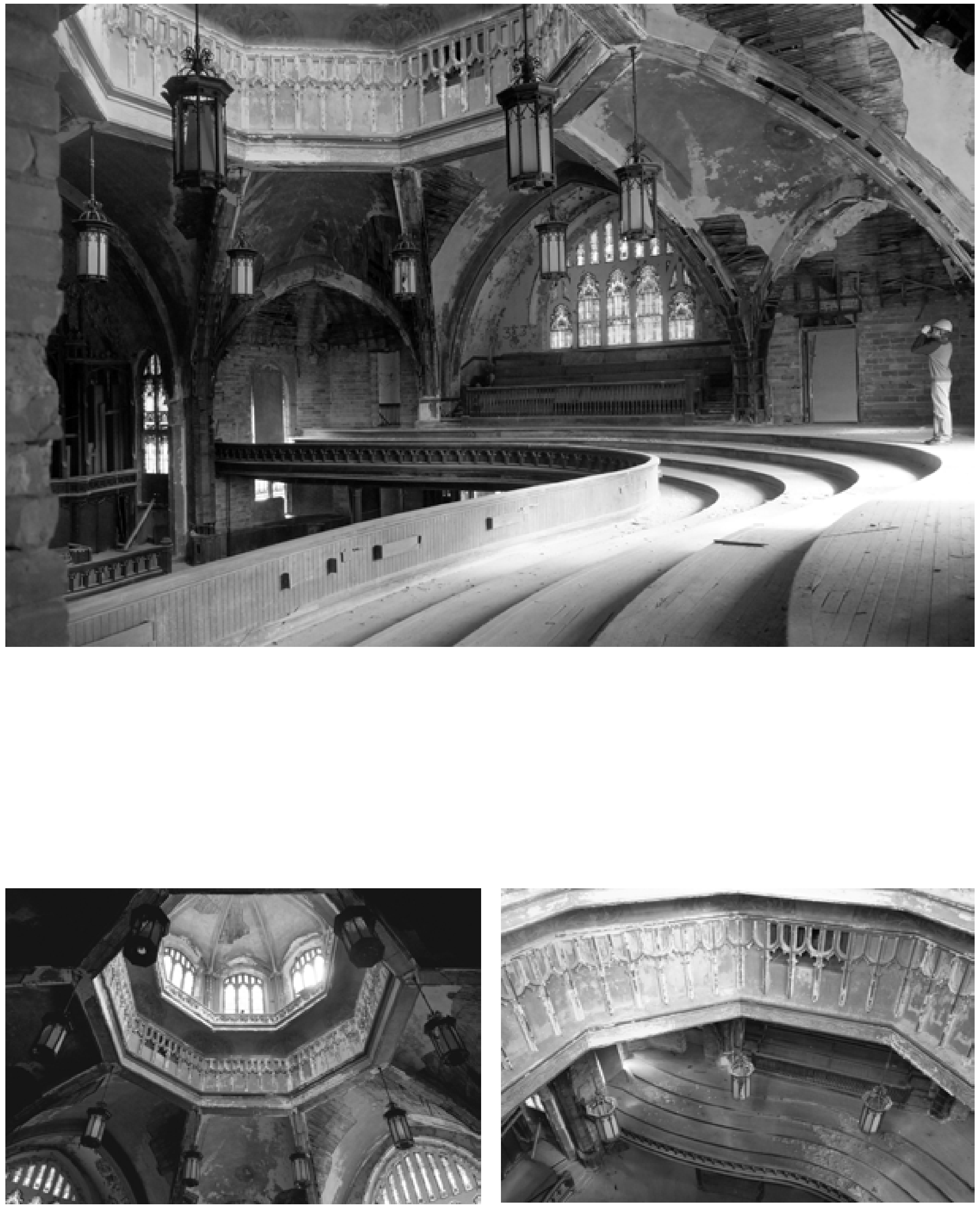


Fig. 7.4 Interiors of the Woodward Avenue Presbyterian Church. Materials are in a severe state of degradation.

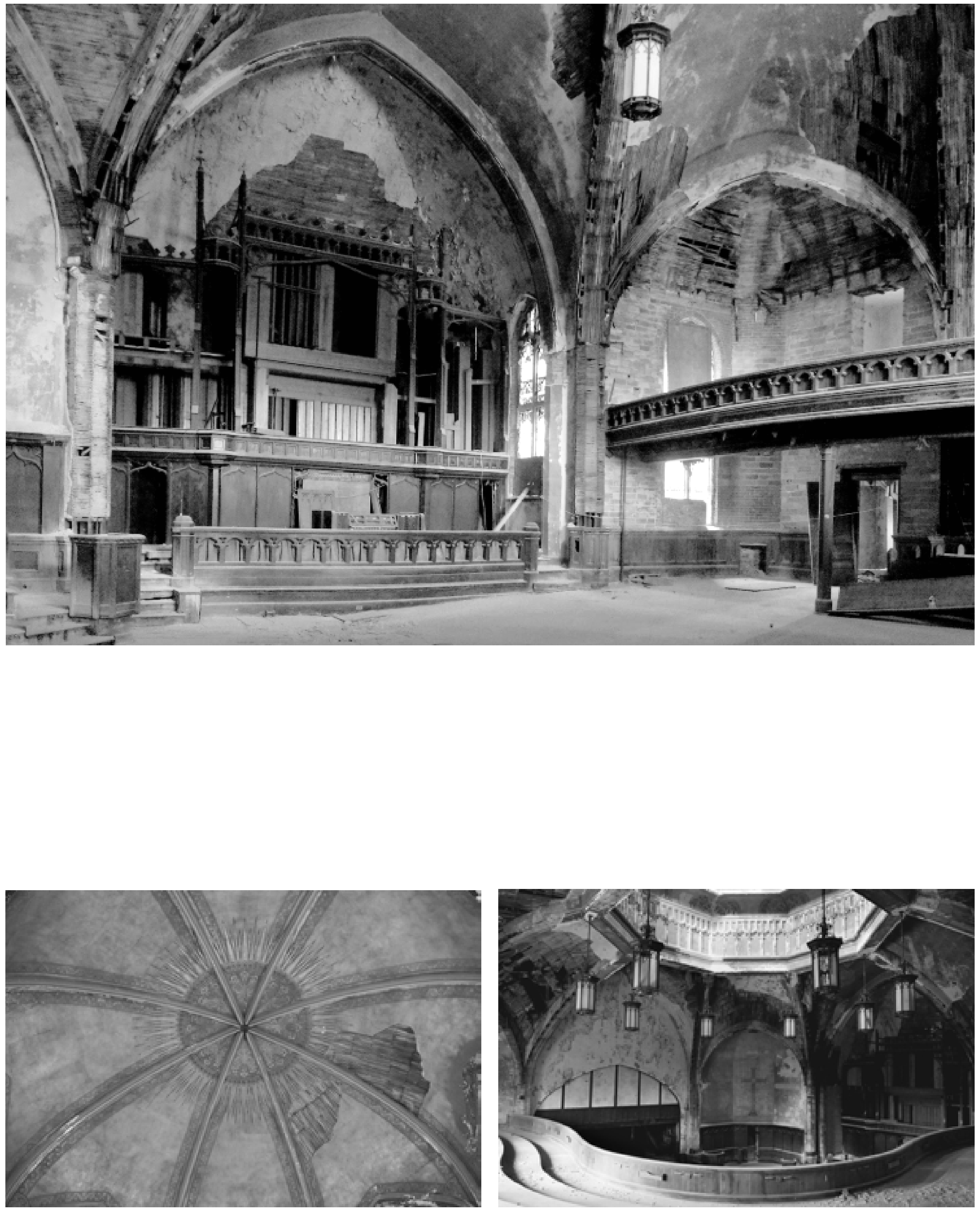


Fig. 7.5 Interiors of the Church. All wooden structures and in particular the mezzanine require maintenance.

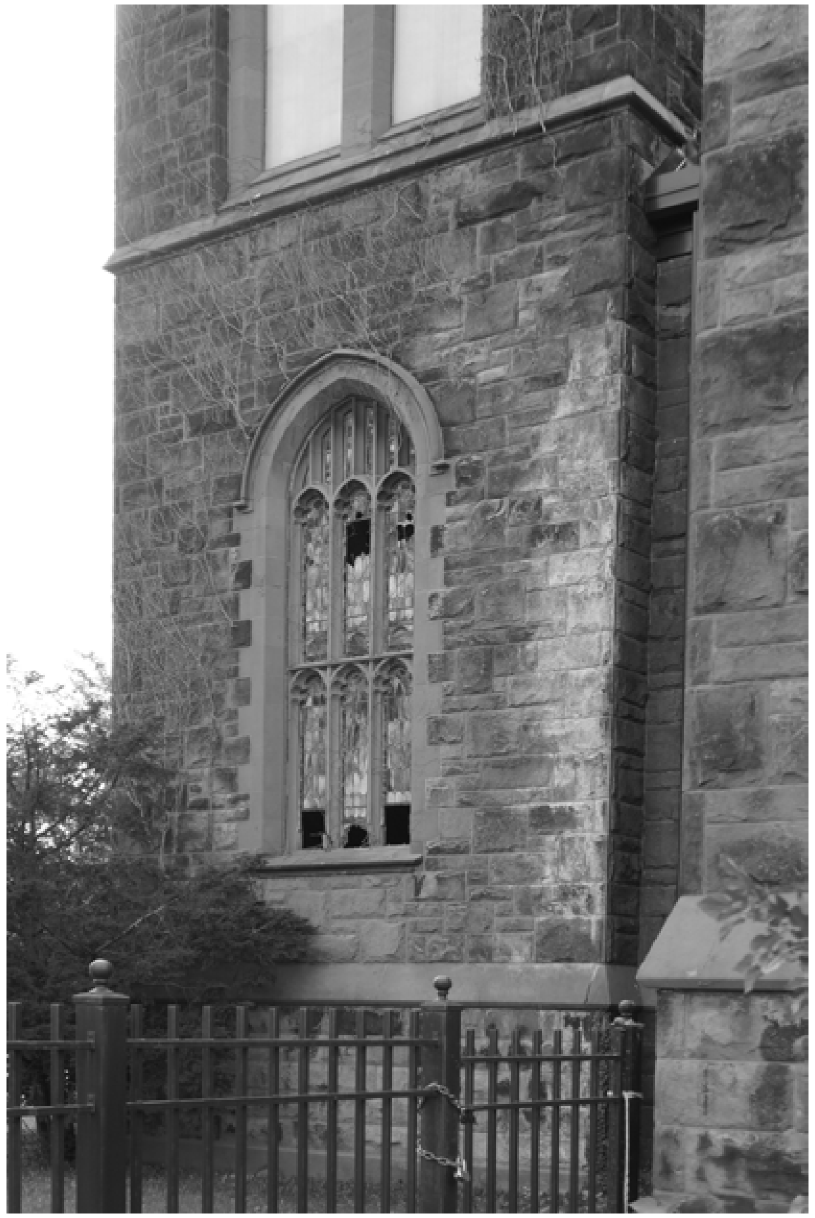


Fig. 7.6 Interiors of the Woodward Avenue Church. Details of the dome and the damagement of the surfaces.

Fig. 7.7 Exteriors of the building. The opening and the surfaces of materials have been degrading over time.

NPS Form 10-900-a
(7-81)

OMB NO. 1024-0018
EXP. 10/31/84

United States Department of the Interior
National Park Service

National Register of Historic Places Inventory—Nomination Form

For NPS use only
received
date entered

Continuation sheet 21 Item number 7/8 Page 22

1. Historic and Common Name: Woodward Avenue Presbyterian Church

2. Location: 8501 Woodward Avenue ~~(at Philadelphia)~~
   Detroit

3. Category: building
   Ownership: private
   Status: occupied
   Use: religious

4. Owner: Reverend Paul M. Gillis and Vestry Board of Woodward Avenue Presbyterian Church, 8501 Woodward Avenue, Detroit, MI. 48202

7. Description:
   Condition: good
   Unaltered
   Original site

The structure is located on the northwest corner of Woodward Avenue at West Philadelphia in Detroit and measuring 184 feet in length and 104 feet in width. Woodward Avenue Presbyterian is a rockfaced, brownstone, modern English Gothic-style church with smooth, contrasting, limestone trim built in 1909-1911. It represents a radical departure in massing and plan from the standard, end-gable-roof-and-corner tower Gothic church type. The essentially square, two-story structure is dominated by a tall, octagonal, stone lantern rising from the center of the roof. The symmetrical, Woodward Avenue facade is composed of two, low, square towers flanking a gabled central section containing the massive, carved-stone-enframed entrance and a Gothic-arched, traceried, stained glass window. The side elevations are dominated by the gabled transepts, which contain full height traceried windows. Adjoining the rear of the church is the two-story educational wing which was constructed at the same time as the church. The design depends upon the contrast between the rough, dark, brownstone walls and the abundant light-colored smooth, limestone English Gothic carving used for the window enframements, the parapets, the gable panels and the portal treatment.

The interior conforms to the Akron Plan auditorium type. Fixed seating arranged in a semi-cricle, both on the main floor and in the curving balcony, focusses on a sanctuary platform and adjacent choir area on an interior wall. The basically square, two-story high auditorium is lit by an open lantern in the center of the vaulted ceiling. The well lighted hall contains dark oak woodwork and pews that contrast with the cream colored walls. Painted decoration made to simulate Byzantine mosaics is used sparingly in the sanctuary and choir areas.

8. Significance:
   Period: 1900-
   Areas of Significance: architecture
   Specific dates: 1908-1911

Fig. 7.8 Documentation on the Woodward Avenue Church. The NRHP reference #82002916, from the *Federal National Register of Historic Places*.

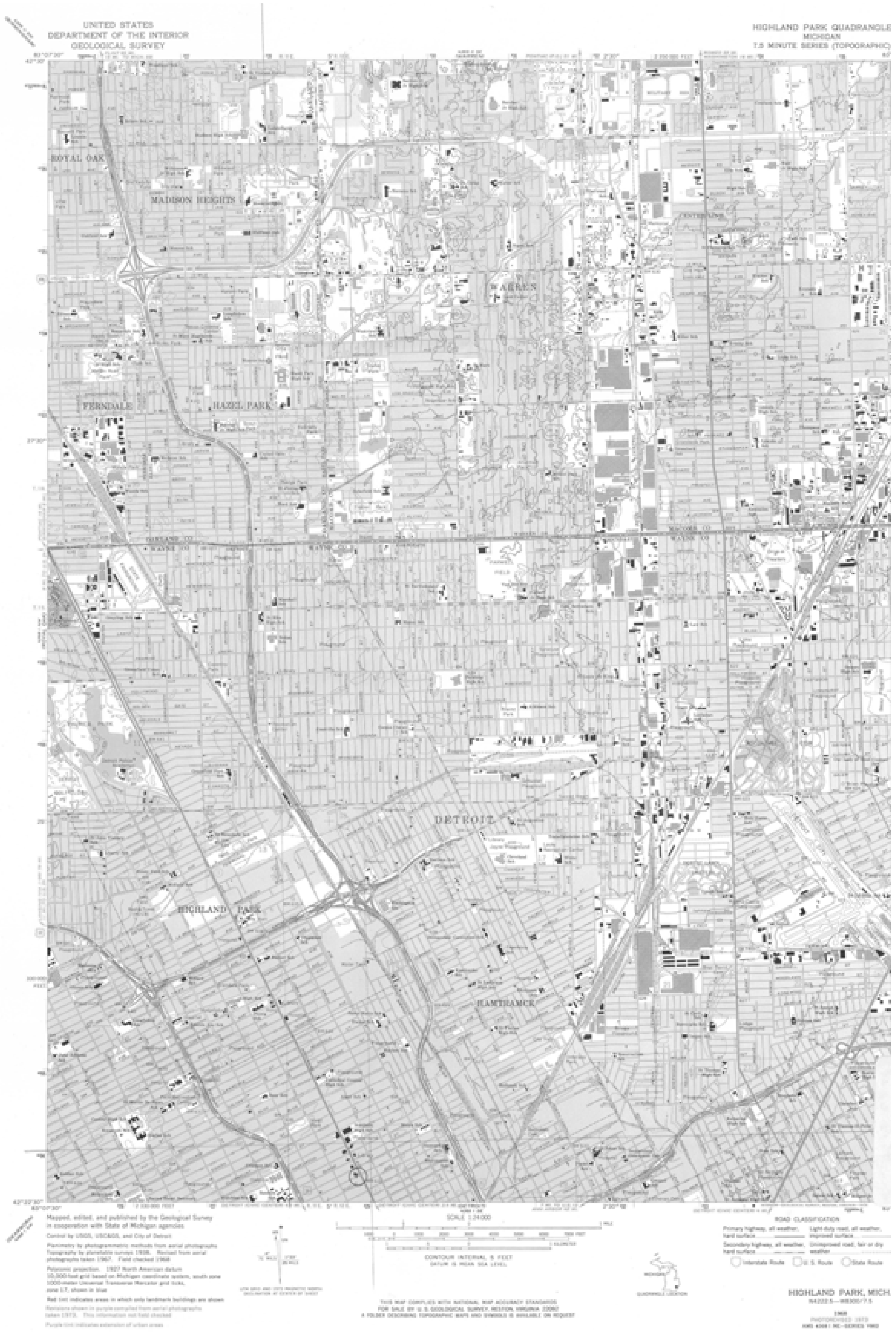


Fig. 7.9 Caption of the picture, from the NRHP documentation. Woodward Avenue Presbyterian Church | 8501 Woodward Avenue Detroit, Wayne County, Michigan, MI. UTM reference: 17/328800/4693620.

Fig. 7.10 Caption of the picture, from the NRHP documentation. Woodward Avenue Presbyterian Church | 8501 Woodward Avenue Detroit, Wayne County, Michigan, MI. Photographer: Leslie J. Vollmert. Date: November, 1980. Negative: Michigan History Division | Michigan Department of State Lansing, Michigan 48918. View: Camera facing SW. Photo: No. 28 of 53.

Fig. 7.11 Caption of the picture, from the NRHP documentation. Photographer: Leslie J. Vollmert. Date: November, 1980. Negative: Michigan History Division | Michigan Department of State Lansing, Michigan 48918. View: Camera facing NE towards organ and pulpit. Photo: No. 30 of 53.

Fig. 7.12 Caption of the picture, from the NRHP documentation. Woodward Avenue Presbyterian Church | 8501 Woodward Avenue Detroit, Wayne County, Michigan, MI. Photographer: Leslie J. Vollmert. Date: November, 1980. Negative: Michigan History Division | Michigan Department of State Lansing, Michigan 48918. View: Camera facing SE toward lantern in roof. Photo: No. 29 of 53.

Phase 2: Selection of the wall gap as a case of damage

The analysis of the building degradation was carried out during two inspections, implementing qualitative photographic and digital quantitative data. A preliminary photographic analysis served to identify the main critical aspects - the structure and the external envelope. Cracks in the windows allowed the rain to wet the stone and wooden elements over the years. Thus, several architectural elements have been subject to a frequency of freeze-thaw cycles, exacerbated by the harsh continental climate of Michigan. Moreover, gaps exist in the perimeter walls, and the layers of the internal vaulted systems are no longer cohesive.

For experimental purposes, a damaged building unit was identified through which to express the potential of a robotic recovery intervention. For the identification of the degradation phenomena (Fig. 7.14), in particular for the elements of the building envelope, reference was made to the synoptic table of the Normal Commission - Standard for Stone Products (Normal, 1991), edited by the Italian ICR (Central Institute for Restoration). The analysis was useful to categorize damages within the building system, mapping areas of the building united by certain characteristics. These damages are the loss of portions of materials and the presence of uneven vertical and horizontal surfaces. The wall gap was used as an investigation field (Fig. 7.13).

Degradation of the stone elements of the external envelope:

- chromatic alteration and surfacing of stains on the casing due to atmospheric leaching and dust deposits due to atmospheric pollution;
- dripping, presence of vertical traces close to gutters and window pallets;
- diffuse crusts and superficial layers of alteration of the stone material due to the action of microorganisms and pollutants;
- surface deposit, accumulation of foreign materials of various kinds with poor adherence to the underlying material;
- efflorescence, formation of powdery substances of whitish color on the surface, consequent to the runoff of meteoric waters and to the action of the wind that accelerates the evaporation of the water;
- lack, fall and loss of parts of the windows, including both glass panels and wooden windows, due to rainwater runoff, wind power transport and lack of maintenance;
- biological patina in correspondence of the threshold elements of the entrance doors, due to the action of microorganisms in the presence of humidity and water.

Degradation of the stone elements of the envelope and of the non-structural internal elements:

- chromatic alteration of the internal wall elements due to the presence of humidity;
- superficial deposit of dust due to the state of abandonment of the church and debris derived from the disintegration of internal cladding elements;
- disintegration, de-cohesion characterized by the detachment of granules under minimal mechanical stress, concerning the internal plaster and the interface between bricks and mortars;
- detachment, solution of continuity between surface layers of the material, both between them and with respect to the substrate, with consequent fall of the same. This type of degradation concerns all the surfaces that were originally plastered. It is caused by humidity phenomena and differential expansion between support and finishing materials, among which there is no longer cohesion;
- gaps, or fall and loss of three-dimensional elements from a wall facing; the most widespread lacunae in the building can be identified in the brick walls on which the internal vaults that converge in the central dome are set;
- lack of wooden elements that make up the floors, the ribs and the warps of the internal vaulted structures, the covering of the pillars, the parapet of the mezzanine choir, and the decorative elements of the dome.

This analysis made it possible to identify an element that has the characteristics suitable to be investigated with a robot fabrication logic. For this purpose it was decided to select a wall gap, or the volumetric lack of a portion of the wall, so it is possible to make speculations on how to reintegrate. The gap is found in a brick septum that is not part of the main bearing structure. The wall defines the height of one of the eight vaulted structures that converge on the sides of the octagonal dome. The gap highlights a multitude of technical aspects to be solved. It has the following characteristics:

- it is a volumetric lack that has been decided to complete geometrically as a recovery action taking into consideration the final architectural image;
- it is located on the first floor level and at a height of 3 meters; the surrounding walls are arranged in space in such a way as to facilitate the simulation of a robotic work-cell;
- it is defined by geometric complexity and presence of undercuts;
- consists of irregular horizontal and vertical surfaces.[23]

23 Analysis of degradation based on the "Raccomandazioni NorMal - 1/88. Alterazioni macroscopiche dei materiali lapidei: lessico", CNR-ICR, 1990, Roma. Available at: http://www.iuav.it/Ateneo1/docenti/architettu/docenti-st/Paolo-Facc/materiali-/abaco_degradi.pdf.

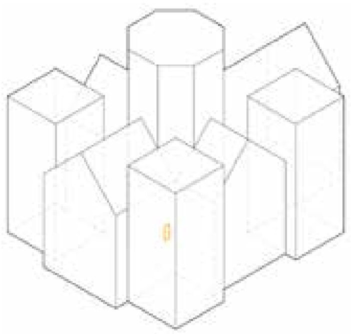


Fig. 7.13 Location of the gap in the building and photographic survey of the damage to the masonry wall and the wooden vault.

Fig. 7.14 Some of the degradation identified in the Woodward Avenue Presbyterian Church, through the photographic survey of the exterior and interior environments. Among others, shortcomings emerge in vaulted structures and in glass surfaces, masonry gaps, surface deposits in internal surfaces and detachment of internal finishing plaster.

Phase 3: on-site data acquisition

The photographic documentation was followed by geometric survey with digital instrumentation (Fig. 7.15, Fig. 7.16), following the procedures from literature (Remondino, 2011). The survey activity was carried out by integrating data obtained from complementary tools (Lercari, 2016).

Three-dimensional textured digital survey TLS (Terrestrial Laser Scanning)

Output: textured point cloud.

Objective: collect the point cloud of the overall building geometry. In order to estimate the accuracy of the photogrammetric survey it was necessary to have a high accurate reference model, for further analysis.

Tool: Leica BLK360 360-degree laser scanner.[24] Revit software to merge digital data.

Methodology: a standard procedure was performed for this phase (Guarnieri et al., 2013) by several point clouds registered in the absolute reference system.The internal volume of the building was reached within the radius of action of the laser scanner, installed on a tripod and positioned according to the relief scheme developed for the building (Cabrelles et al., 2009) both on the ground floor and on the first floor (the choir floor is deteriorated but can be walked on). The digital data was then combined to maintain areas of overlap to avoid measurement errors. The survey of the external volume has not been carried out because, for the purposes of this research, it requires to a lesser extent maintenance interventions.

Close-range fast survey

Output: mesh digital model.

Objective: create meshes of decorations, structural details, and cases of damage that were out of range for the scanner's visual cone. Comparison was carried out for the dimensional deviation between the two digital data acquisition modes. This, to understand if the close range survey is reliable during an emergency condition that requires quick interventions to secure the building.

Tool: Structure sensor[25] collected geometric data and simultaneously operated through a photogrammetric technique. It was plugged to a mobile a tablet.
Methodology: digital acquisition of the elements of the church subject to degradation, with an augmented reality visualization of the portions in which the scanning is taking place. In particular, these were details or decorations. Data collection took place by manually moving the tablet around

24 Leica BLK360: https://lasers.leica-geosystems.com/blk360.
25 Occipital Structure sensor: https://occipital.com/.

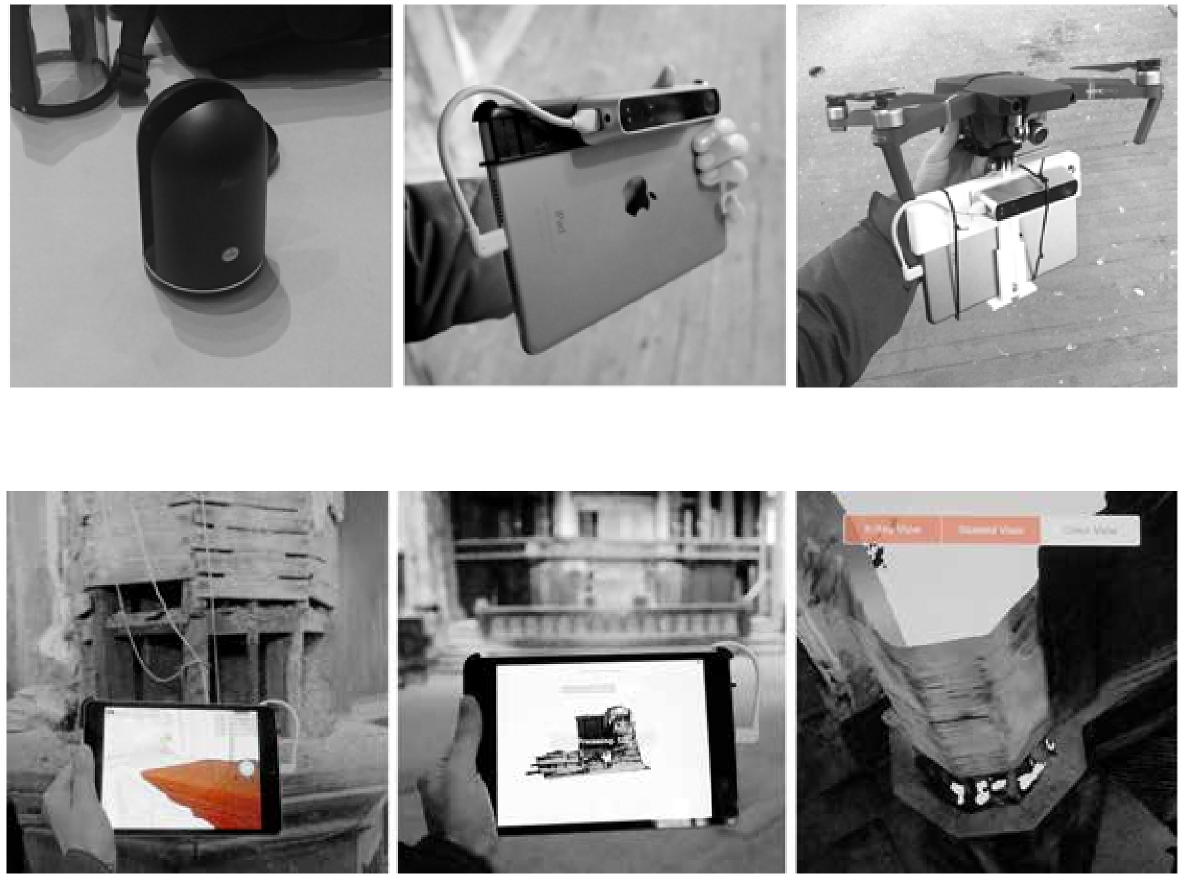


Fig. 7.15 Above: tools used for the digital geometric survey of the church: 360 laser scanner, occipital structure sensor installed on a tablet and in turn on a drone. Below: manual scanning of the elements in state of degradation, real time display of the digital models and survey sent by the instrument via augmented reality display.

the object to be detected, returning the mesh built in the software environment in real time. The software itself provided guidance on how to orbit the target object.

Experimental survey RPAS (Remotely Piloted Aircraft Systems)

Output: set of images merged with photogrammetric technique and a mesh digital model.

Objective: integrated geometric data of inaccessible areas related to a site culturally relevant (Hashim et al., 2012).

Tool: Drone,[26] Structure sensor installed on a mobile tablet.

Methodology: an RPAS[27] procedure was performed for this phase. Initially the sensor connected to the ipad was connected to the drone. The drone was manually driven around the elements being analyzed to collect digital dimensional data (Nex and Remondino, 2014), especially of the central dome. The drone was integrated with accessory equipment. The flight path was programmed and photographs taken at regular intervals. By acquiring several images with both vertical and oblique camera's optical axes (Aicardi et al., 2016), to make a photogrammetric reconstruction possible (Bolognesi et al., 2015). In total 4 different flights were carried out.

26 Drone DJI Mavic Pro: https://www.dji.com/it/mavic.
27 RPAS means Remotely Piloted Aircraft Systems. Drones belong to this category. The application of small scale aircraft technologies is currently under study in the field of architecture. RPAS indicated a methodology used to carry out surveys in wide, dangerous or inaccessible areas. Drones can be referred to with the acronym UAV, unmanned aerial vehicles. In 2009, the dissertation "UAV photogrammetry" from Henri Eisenbeiss was considered one of the first major work in regards to using UAVs for Cultural Heritage purposes. Since that time, the popularity of using the platform of UAVs for documentation through UAV photogrammetry, has increased due to technological advances and the ease at which UAVs can be purchased, with particular attention pointed at Cultural Heritage.

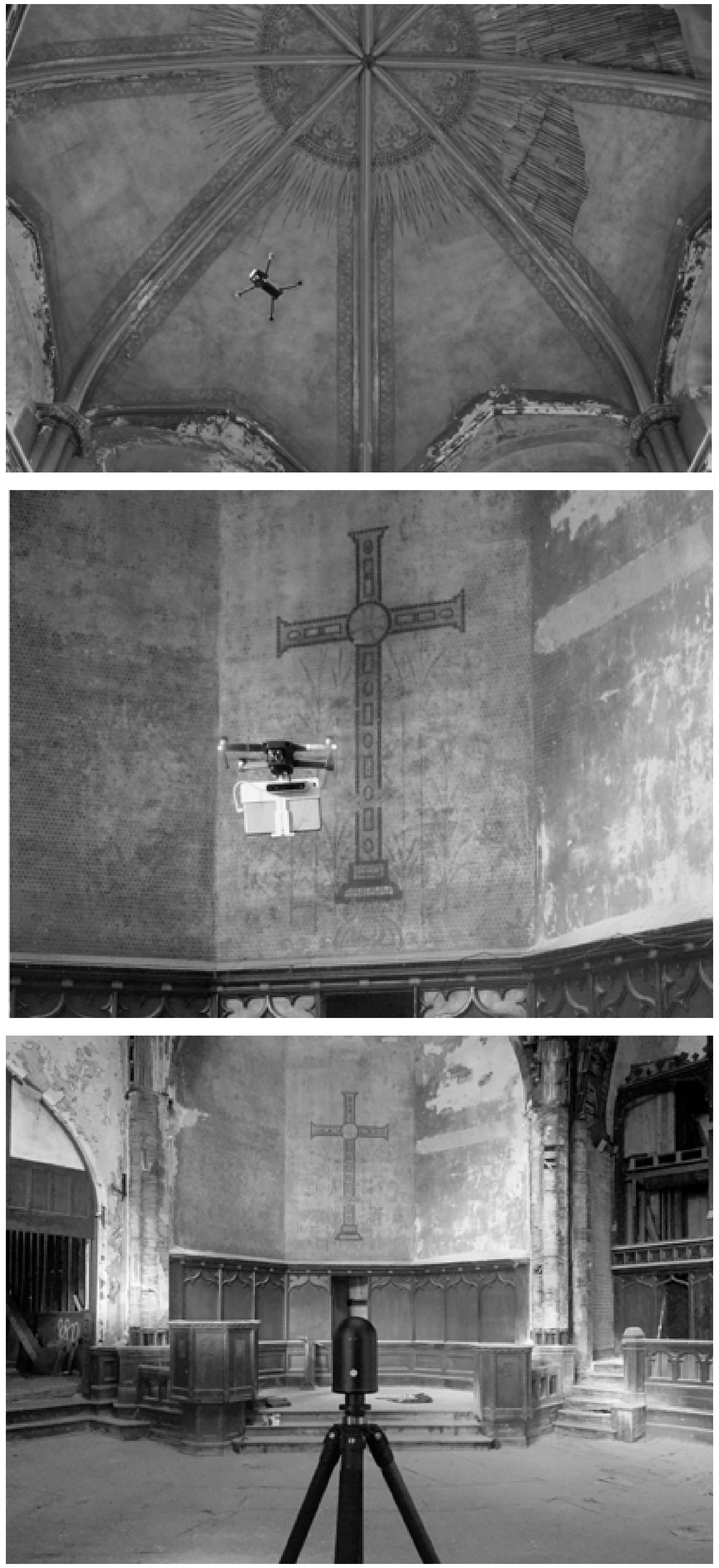


Fig. 7.16 Use of the 360 laser scanner and photogrammetric survey with the drone plugged to a lidar sensor.

Phase 4: digital data analysis and elaboration

Three-dimensional textured digital survey TLS (terrestrial laser scanning)

The digital survey made it possible to obtain the three-dimensional model of the church's internal volume,[28] expressed as a point cloud (Fig. 7.17), integrated by the photogrammetric data and then textured. It constituted the most precise information collected and served not only to understand the geometry of the building but also as a dimensional reference for the other relevant methods. The three-dimensional model was uploaded online in an open source platform. The accuracy of the instrument allowed us to collect digital data with an accuracy of 6-8 mm, inversely proportional to the distance of the instrument from the target.

Close range fast survey

The quick survey was configured as an operating methodology complementary to the overall survey elaborated through the use of the laser scanner. In fact, the speed of execution was effective to start the planning phases. For experimental purposes it was considered that the accuracy of the instrument was sufficient to perform interaction tests with the robotic instrument. The measurement deviation, in relation to the relevant distance, was evaluated between 0.5 or 1.2%.[29] The textured mesh of the wall portion in which the gap is present was therefore used for the subsequent phases of the experiment.

Experimental survey RPAS (Remotely Piloted Aircraft Systems)

The survey performed with the drone was partially usable. The preventive planning of the flight path and the setting of the intervals for taking photographs using the drone camera itself (Federman et al., 2017) was effective in obtaining systematized material for a photogrammetric reconstruction (Fonstad et al., 2013) using the PhotoScan software. The operating limit was observed at the time of use combined with the sensor for digital mesh construction. With this configuration, the drone was too heavy and generated vibrations that compromised data acquisition. Since it was not a static object but needed the thrust of the wings to be in flight, it caused the spread of dust and sediments in a diffuse way. Excessive proximity to surfaces caused dust and sediments to be pushed back by the force of the air. Finally, manual drone driving in manual mode required skill as well as knowledge of the instrument. The use of RPAS was carried out as workflows and according to best practice guidelines[30] currently defined by the scientific community. If optimized, this technology

28 Woodward Avenue Presbyterian Church WebModel: http://www.webmodel.space/.
29 Precision of the Structure Sensor: https://support.structure.io/article/158-how-precise-is-the-structure-sensor.
30 See the research carried out at the Department of Engineering, University of Ferrara for the survey of the Delizia Estense del Verginese. See also the survey of the Prince of Wales Fort carried out by the Departments of Civil and Environmental Engineering, Mechanical and Aerospace Engineering of the Carleton University, with the consultancy of the Heritage Conservation Directorate in Canada.

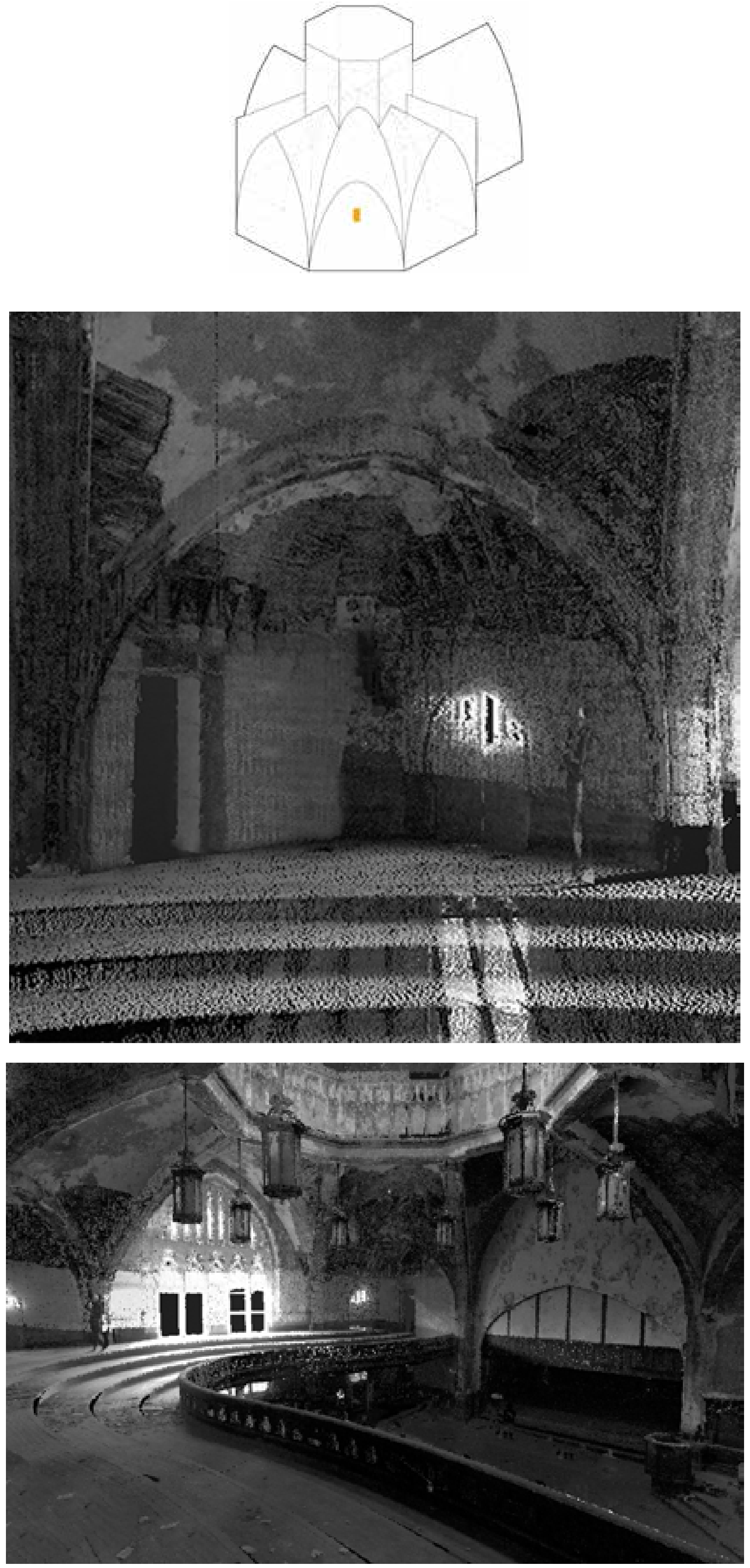
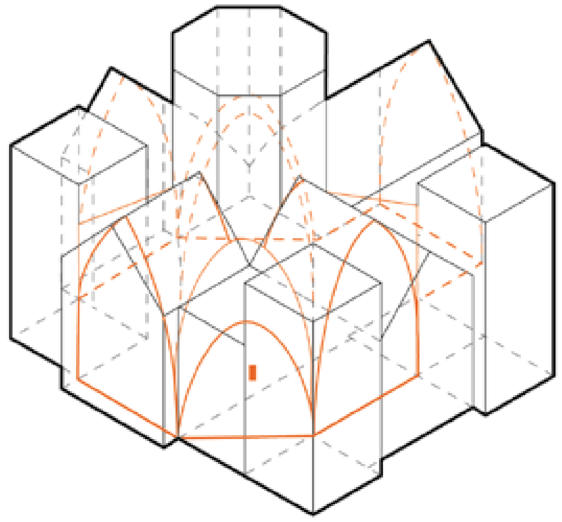


Fig. 7.17 Cloud of points of the church and in correspondence of the “lacuna” object of analysis.

Fig. 7.18 Above: close range survey: 1) images collected to texturize the 3D model; 2)textured mesh; 3) clean digital model. Below: cloud of points of the church and in correspondence of the "lacuna" object of analysis.



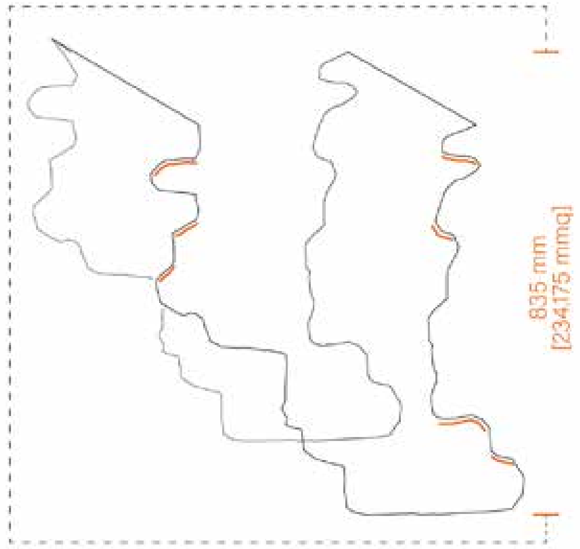


Fig. 7.19 The gap has an irregular geometry both on the vertical and on the horizontal plane. The previous diagram shows the segments that are found in the undercut. At the geometrical level these constitute elements of complexity for the additive manufacturing process, which involves the deposit of consecutive layers by an end-effector that usually has no movement constraints on the vertical axis z. The undercuts represent an opportunity to show graphically the procedural limits of additive manufacturing within a pre-existing perimeter. Another potential limitation to consider is the size of the gap, whose height is just under one meter. This does not affect the quantity of material necessary for defining the volume, but also the manufacturing timing; from literature, in fact, the optimal thickness of the layers for the extrusion of clay-based materials, the realization of outputs at scale of architectural technological units varies between 0.4-0.8 mm. In reality, the gap is part of a brick wall. For this experimental phase the perimeter of the missing portion was taken into account and not the size of the brick courses, which can be inserted as a design variant in a later phase of the experimentation.

has the potential to replace human intervention in heritage documentation operations in emergency situations or in inaccessible areas. This approach is complementary to and in continuity with the future scenario of using the robots directly on-site for restoration procedures. The comparison of digital data was followed by the refinement of the mesh and the removal of superfluous information. The three-dimensional model (Fig. 7.18) was managed using the Rhinoceros modeling software. Then the CAD / CAM transition process followed the modeling and the plug-in for RhinoCam[31] was used, through which it was possible to set the file for the physical realization of the digital model.

The selected wall gap has an irregular geometry both on the vertical and on the horizontal plane. The previous diagram showed the segments that were found in the undercut (Fig. 7.19). At the geometrical level these constitute elements of complexity for the additive manufacturing process, which involves the deposit of consecutive layers by an end-effector that usually has no movement constraints on the vertical axis z. The undercuts represented an opportunity to show graphically the procedural limits of additive manufacturing within a pre-existing perimeter.

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Phase 5: setting up of the experimentation: the definition of an offsite mock-up

Scientific research is directing experiments in the robotics field towards the use of machines in situ (Keating and Oxman, 2013). The idea of using industrial robots on-site is therefore still reserved for academic research. On a theoretical level, this research suggests a workflow based on the installation of an industrial machine on-site. On a practical level, the following obstacles can be recognized:

- the failure to use robots in the construction site and therefore the lack of a shared methodology on-site that takes into account safety, certifications, maintenance, transport costs and installation times;
- the lack of a best practice already formulated which suggests how to relate the pre-existing work environment (ie a broken-down architecture, building site needs) (ie raising the machine to a height above the floor), the labor required for each stage of the process;
- the lack of a team of people trained in robotics applied to pre-existing architecture;
- the lack of a budget, in this experimental phase, to generate an attempt to systematize the process;
- the acknowledgment that today the use of industrial robotic systems for architectural recovery is

31 RhinoCam, a plug-in for Rhinoceros for CAD-CAM applications: https://www.food4rhino.com/app/rhinocam.www

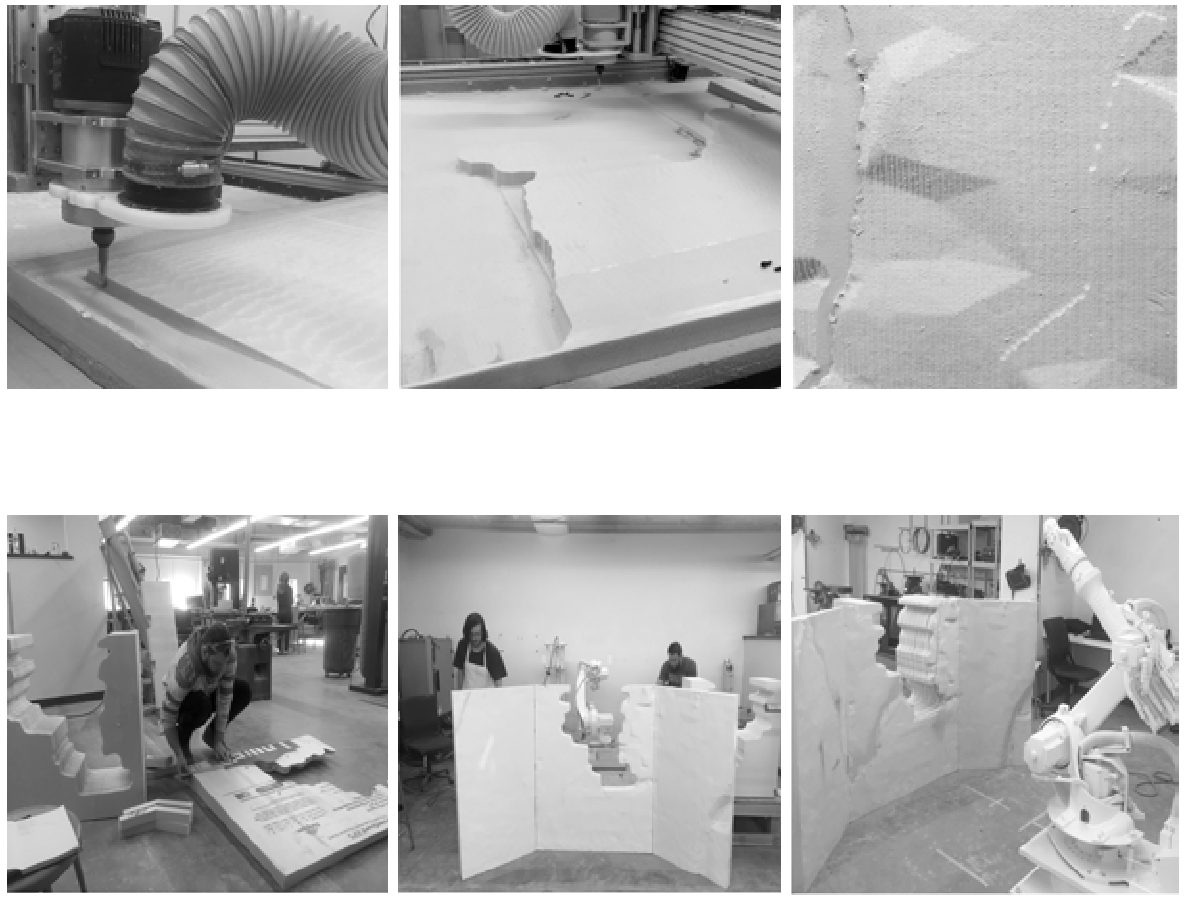


Fig. 7.20 Above: realization of the wall prototype cutting foam with a CNC. Assembling of the foam wall prototype. Below: set-up of the experimentation: Robot, foam wall prototype on the robotic workcell.

more expensive than the traditional systems used to carry out the same operation; As labor costs increase with a decrease in skilled crafts people this equation may change quickly.
- the lack of a feedback-loop system (real-time updating with digital return of the changes in the work area in which the robot operates and the management of measurement tolerances), essential if the proposed experiment involves an additive process, with consequent modification of the geometry of the gap;
- the availability of a reduced range of materials to be used for robotic additive manufacturing. Or the lack of an engineered material suitable for operating through extrusion on masonry surfaces from which the need to develop an interface surface between existing and new construction can digitally fabricated;
- the circumstantial condition for which the experimental activity took place in Michigan in the winter months, in a context in which the temperatures drop to -40C, making it impossible to set up the work inside an unheated, uneven shell.

It was decided to completely automate the production through an offsite production in a controlled laboratory environment. For this purpose, it was necessary to reconstruct the geometry of the wall to carry out the kinematic tests of the robot and the extrusion tests. It was decided to use foam as a material to be assembled for the definition of the wall context because it was inexpensive and suitable for absorbing the impact of any collisions with the robotic machine without damage (Fig. 7.20). Operationally, the 3D model of the wall mesh was divided into 5 cm thick vertical sections, based on the thickness of the commercial foam material. This procedure made any disassembly easy. The sections were processed in RhinoCam to obtain a file compatible for cutting using a CNC. To optimize the use of the material and taking into account the dimensions of the robot, it was decided not to work on the gap at an altitude of 3m (actual height of the wall gap). The height of the prototype was 1.5 m and remainsedon a 1: 1 scale. Each section required 20 minutes of numerical control machine work, for a total of 3 hours and 40 minutes to complete. A wooden platform was built around the robot to display its work cell, within the maximum extension of its axes.

Phase 6: evaluation of tools and performances of materials

Tool analysis and motion settings

Technical checks were carried out to define the daily operating limits of the robot in the laboratory environment. Through the use of a thermal imaging camera[32] the mechanical behavior of the 6 axes was monitored, at 30 minute intervals during the execution of a simple script. The engine temperature test was always less than 30 degrees during the entire period of activity. A misalignment of the performances occurred with regard to the hardware-software relationship. Following multiple checks, the computational core has stopped reading the codes and transmitting them to the teach pendant after 8 hours of use, requiring a forced restart of the controller and defining the maximum hours of

32 Thermal Camera Flir used to monitor the robot's mechanical behaviour: https://www.flir.it/products/flir-one-pro/.

operation. There were some forced interruptions during the tests due to the maximum capacity of the files readable by the operating system, equivalent to 65 Kb, or 703 lines of code. This limitation was due to the fact that the robot used at LTU was previously used in the Hummer[33] industrial assembly line for repetitive welding operations that require relatively simple programming. To proceed with the experiment, the optimal mode for executing the code was chosen, between T1, T2, AUT and AUT EXT.

T1 (Manual Reduced Velocity)
- For test operation and setup work
- Velocity in program mode max 250 mm/s
- Velocity in jog mode max 250 mm/s
- Jog mode: available for testing/verification
- Operator safety (safety gate) was not monitored

T2 (Manual High Velocity)
- For test operation
- Velocity in program mode corresponded to the programmed velocity and > 250 mm/s is permissible
- Jog mode: not possible
- Operator safety (safety gate) was not monitored

AUT (Automatic)
- For industrial robots without higher-level controllers
- Velocity in program mode corresponded to the programmed velocity
- Jogging with the jog keys or Space Mouse was not possible

AUT EXT (Automatic External)
- For industrial robots with higher-level controllers (PLC)
- Velocity in program mode corresponded to the programmed velocity
- Jog mode: not possible

The T1 mode was excessively slow and required that the keys for starting the robot kinematics be kept continuously pressed for safety as part of the teaching or training mode. The T2 mode required the programming of the speed which will be executed as indicated in the code. Although this setting allowed for the calculation exactly the timing of implementation, it required a deep knowledge of the result to be achieved, but it was not always optimal for the testing phases. The AUT EXT mode was usually used in more complex industrial systems equipped with sensors in communication with each other. The AUT mode instead, allowed for the reading of the code loaded on the robot software automatically and adjustment to the speed percentage on the Teach Pendant. In this way it was possible to adjust the robot movement speed starting from 3 mm/s and at the same time to manage the extruder speed connected to the end-effector.[34] The 65 KB limit was not a problem since the

33 American cars brand based in Detroit 1992-2010. After 2010 the company was absorbed by General Motors: https://www.gm.com/.

34 Based on the state of the art, the relation between the robot and the extruder speed is based on the relation: Espeed = Rspeed (m/s) *K *N *L, Rspeed is the robot speed, K is a constant equal to 1000, N is a value related to

state of the art already expects to interrupt the additive manufacturing at regular intervals to allow the material to dry, acquiring the resistance necessary for affixing the subsequent layers.

Material analysis: clay extrusion

The diffusion of 3D printers and robotic manufacturing favored the definition of a testing ground called large-scale robotic additive manufacturing. In this context, space has been given to the use of clay materials, since they have numerous advantages defined by mechanical and structural properties and by the fact that they are readily available, biodegradable and low cost. This defines the concept of clay robotics[35] for which process automation and increased production efficiency are accompanied by an exploration of the potential offered by the introduction of robotic manufacturing together with a generative computational process that allows the use of the performance as design inputs within a data-driven process (Figliola, 2018a). In this logic, for example, the Pylos[36] project was developed in 2015 at the IaaC, Institute of Advanced Architecture of Catalonia, which explored the use of an extruder installed on a robot for the construction of technological units on an architectural scale using a natural clay-based material. This process allowed the production of columns with a customized geometry over two meters high through precision and quality of surface treatment. The knowledge gained with this project advanced research with the experimental prototype TerraPerforma.[37] The assembly of on-site technological units was experimented to define a hypothesis of external vertical performative closure from an environmental and structural point of view (Dubor et al., 2018). The project's performance was the morphology of the prototype's structural pattern, designed to reduce the surface temperature and therefore decrease the energy load of the components through self-shading.

The aforementioned projects investigated digital robotic fabrication methods for the realization of study prototypes through additive manufacturing processes for a possible future application in architecture[38] (Sollazzo et al., 2018). These experiments used a low engineered material because

the dimension of the extruder, and L is the offset of the layers.

35 Clay robotics and the future of architecture: https://www.theguardian.com/artanddesign/architecture-design-blog/2014/aug/08/clay-robotics-architecture-chilterns-farm.

36 Pylos project: http://pylos.iaac.net/ and https://iaac.net/project/pylos/. The Pylos project at IaaC benefitted the consultancy of Dshape, company specialized in material engineering. The mix for the large-scale robotic additive manufacturing included clay, sodium hexametaphosphate, and cellulose. The resulting bulk material has fluidifying properties due to a process of water softening obtained by lowering of dissolved salts which can precipitate like carbonates.

37 TerraPerforma is a prototype realized within the event Open Thesis Fabrication 2016/2017. For further information see: http://www.needlab.org/terraperforma.

38 The use of clay in architecture comes from a long vernacular tradition. Among the different techniques we can mention punctual elements (adobe brick) or linear technological units (pisè or tapial or rammed earth). The adobe is a rectangular material made from earth and organic materials. Rammed earth, also known as tapial in Spanish or pisé (de terre) in French, is a technique for constructing foundations, floors, and walls using natural raw materials such as clay, lime, or gravel. It is an ancient method that has been revived recently as a sustainable building material.

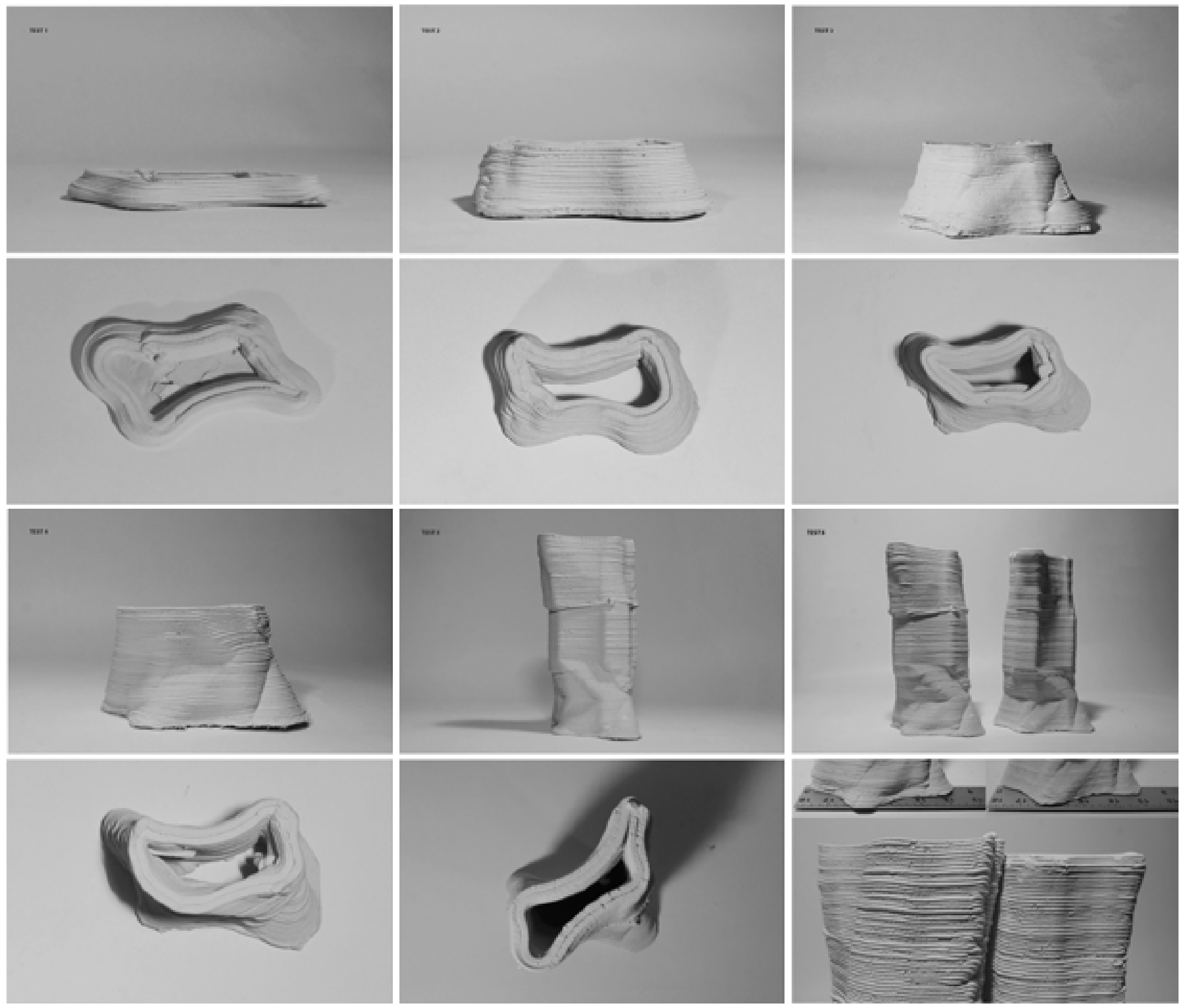


Fig. 7.21 Above: tools used for the clay testing for extrusion. Below: testing of clay extrusion by using the delta 3D printer available at makeLab.

it was versatile and met the needs of the project that a concept test required. For a more elaborate experimental next step it was necessary to use high engineered materials, not yet commercially available. It was decided to use industrially processed clay[39] as an inexpensive material, for printing a volume of 835 cm high within a 40 cm deep perimeter printing path. In addition to being economical, clay is reversible, recyclable and readily available. Finally, at the time of extrusion the clay was in the state of viscous solid, so it was able to adjust to the geometry of the surface on which it was deposited, minimizing dimensional tolerances. This encouraged discussion of the characteristics to be considered for future research on materials engineering for robotic additive manufacturing and, in this research context, for materials that are suitable and compatible for interventions on the built environment. The research proceeded with the definition of the optimal mixture between industrial ceramics and water, with which the material was impregnated to make manual processing possible. For this purpose, additive manufacturing tests[40] were carried out at the makeLab[41] using the delta 3D printer to produce objects on a design scale and to study the behavior of the clay during the extrusion and drying phases (Fig. 7.21).

The clay mixtures used for robotic additive manufacturing at the University of Michigan were used as a reference. An industrial product of the RO-99G high-fire porcelain w / grog[42] type was used, to be mixed with water to check the consistency. Instead of mixing clay, feldspar, flint, and silica manually, it was decided to use raw porcelain, premixed with grog. Grog "is clay which has been fired then ground up. It is used to reduce shrinkage in clay bodies".[43]

Six clay extrusion tests of small-scale objects were carried out, respectively defined by layers of thicknesses between 2 and 3 millimeters, with different water content. These printing tests were sufficient to obtain a material that withstands under its own weight for a complete extrusion cycle

39 Industrial clay, differently from the natural clay, requires to get dry and be baked to reach consistency.

40 The additive manufacturing tests were carried out by the makeLab research intern Breanna Scranton.

41 In the past, the makeLab developed a recipe for small scale clay extrusion based on a mix of different clay typologies. The mixture was composed by: 15% water; 2% darvan; 10% old mine #4; 32,8% grolleg; 15,5% feldspar, and 24,7% flint clay #295. Darvan is a deflocculant that is similar to sodium silicate. It is weakens the electrical attraction between clay particles and thus acts as a thinning agent in slips and as a general dispersing agent for clay bodies and glazes. It is mainly used to enhance the fluidity of casting slips and maintain or slow the shrinkage rate. OM4 (old mine 4) is a fine-grained ball clay with high plasticity and strength. It is an industry standard. It is variable in nature and tends to be more vitreous than some of the more refractory ball clays that are available. It has some soluble salts which can give a brown coloration to the surface, so barium carbonate may be needed to precipitate these. Grolleg is the industry name for a blended english-china clay, which features plasticity, low titania content and high flux content, low shrinkage and blue-white fired color. It is appropriate for making translucent throwing or casting porcelains. Feldspar is a high quality potassium/sodium/calcium aluminum silicate ground to 200 mesh for ceramic applications. Carefully beneficiated and controlled for quality, G-200 offered high potash content and low iron oxide per unit of alumina. Flint clay is a smooth, flintlike refractory clay rock composed dominantly of kaolin, which breaks with a pronounced conchoidal fracture and resists slaking in water. It becomes plastic upon prolonged grinding in water, as in an industrial wet-pan unit.

42 The weight per unit volume of the material is 2,5 kg/dm3.

43 Grog 200 mesh. See: https://shop.clay-planet.com/grog---20mesh-1-1.aspx.

which carries an object included within a 40x40 cm printing area at a height of 40 cm. Furthermore, the compound did not present problems of shrinkage during the drying process. The same formula did not present any problems when the nozzle was replaced with an 8 mm diameter nozzle for a first large-scale extrusion test. Extrusion with such thick layers requires the use of a larger extruder. The delta printer is 30 cm long and can contain 0.5 dm3 of material, or 8 refills were needed to use a 25 lb. raw porcelain box. 0.5 dm3 correspond to a 10x10x17 cm parallelepiped of which only the perimeter was extruded. For this reason the extrusion necessary to bridge the building gap required the use of a customized scaled-up tool, supported by the kinematics of the robot.

HARDWARE	SOFTWARE
delta 3D printer	rhinoceros (modelling)
clay extruder (tank and nozzle)	grasshopper (parameters setting)
compressed air system (60 psi)	repetier (programming)
arduino microcontroller	ida (processing)

Phase 7: tool making

“To give work substance, we require a medium. The actions of our hands, eyes, and tools must be mediated. When the tools are complex, when the artifacts produced are abstract, or when tools provide the only means of access to the medium - all common conditions in high technology - it can be difficult to say where a tool ends and a medium begins [Malcolm McCullough, 1996]

Robotic end-effectors used in academic research are not yet commercially widespread and the market demand itself is still being defined. As an academic experiment, the decision to build a custom tool tested the process of digitization that future work must confront in the Fourth Industrial Revolution. The approach used was that of the "first build your tool" (Aish, 2013) which, in line with the transformations induced by the post-digital era (Figliola, 2017), allows a designer to customize the manufacturing process and then customize production by changing the tools and technologies used. Given a small market demand for the specific tools in conservation, future work in this area will also need to create custom tools as an initial phase until common understanding is achieved. The design of the end-effector guarantees the ability to manage the production process at the moment of CAD / CAM transition within a “digital continuum” (Leach, 2002) for which the construction of material systems does not depend on typological conventions or standards, but is the result of a process in which “the tools define the materials that constitute the form and not vice versa” (Figliola and Battisti, 2017).

The development of this tool production activity left room for theoretical speculation on the relationship between thinking and making, hybridizing the role of the researcher that through the theoretical study "makes through thinking" with that of the craftsman that "thinks through making" (Ingold, 2013) and increases knowledge through observation and experience (Polanyi, 1966).

Thinking through practical experimental activity allowed for "learn by doing" through a medium[44] which created a sense of a continuum of possibilities (McCullough, 1998). The design of the end-effector has led to the awareness that its operation was aimed at the precise execution of the material system to be implemented through the robot's kinematics. Its use is therefore not directly influenced by tangible experience and manual dexterity, but largely by a set of digital knowledge.

As Robert Aish argues in *First Build Your Tools,* "tools do not exist in isolation. Tools require complementary skills to be effectively used" (Aish, 2013). An experienced craftsman knows how to choose the right medium and to push it as far as it will go and no further. Instead, the artisan researcher who operates in the era of computational thinking, exercises an integrated design that expresses digital complexity in a single process that goes from the ideation phase through the elaboration of algorithmic digital models to the constructive one.

As Matthias Kohler explains in a dialogue with Mario Carpo, "in such a scenario an architectural blueprint will become a dynamic, procedural one rather than a static, geometrical one. Instead of designing through the means of geometry, you design the characteristics of your building through skilful constructive coding" (Carpo, 2014). The compression of the distance between design and production[45] inherent in the CAD / CAM evolution allows for the development of a material sensitivity that belongs to the artisan experience (Picon, 2014) through the medium of the robotic machine, which eliminates the abstraction of digital design processes. This abatement of the limits that define the different skills of the actors involved in the construction of architecture brings the theoretical discussion to be interested in the renewed role of the contemporary architect, whose immaterial presence does not stop at mere representation, "we do not make stuff, we make drawings of stuff",[46] but fits into the responsive mechanisms of automated machines. This opens a breach in digital architecture where it steps out of a tight corset of complex geometries and stylistic formalisms into a radically materially embedded design practice. The tools available today allow the architect to conceive and make at the same time, as the master-builder of the Renaissance. The master-builder had the skills to fully create artifacts by combining the roles of architect, builder, product engineer, and material scientist.

The researchers involved in this experiment operated by updating the role of the master-builder, acting as master controllers (Kieran and Timberlake, 2004), able to customize material and digital processes, acting as digital / algorithm builders and cyborg designers (Picon, 2014) whose intentions are materialized through the action of powerful artificial arms. The prevailing evolution with respect to the model of the past lies in the fact that the master-builder generated a construction-aware design,

44 In the book *Abstracting craft: The Practiced Digital Hand* Malcolm McCullough explains: "The actions of our hands, eyes, and tools must be mediated. The word "medium" has many meanings. Often it signifies a class of tools and raw materials. If a tool is kinetic, and under active human guidance, a medium is static, and passively presents limits to human control".

45 Mario Carpo's talk. The Second Digital Turn at Google: https://www.youtube.com/watch?v=UVerq5DSdKU.

46 Matthias Kohler in conversation with Mario Carpo in Fabricate 2011 - Making Digital Architecture.

so the formal generation incorporated knowledge and experience with respect to construction methods, materials, economic aspects, structural performance, sequences of installation and dimensional tolerances. The current technical possibilities, on the other hand, allows for the break ingaway from standardized production methods and work in the logic of fabrication-aware design (Pottmann, 2013), for which the geometry does not constitute a limit for the implementation and the digital processes are optimized and informed with limits planning to be established each time, based on the characteristics of the project outcome. Learning by doing, in this case making an extension of a robotic arm, has meant the customized design of the tools to achieve the design objective, the definition of the manufacturing process takes into account the tools already available on the market and the need for building new tools for which a democratization process has not yet been implemented.

The following pages document the creation of the robotic extruder end-effector. This process included four tests for the design and fabrication process. The information necessary for the construction of the extruder was collected by interviewing professors and experts in the sector and drawing on the digital models available on open source platforms.[47] The documentation describes the hardware and software tools used, the robot settings during testing, and the reasons why it was necessary to reiterate the construction process and make necessary changes for its ultimate success.

47 Thingiverse (website dedicated to the sharing of user-created digital design files) - Mechanical Clay Extruder: https://www.thingiverse.com/thing:3142561.

TEST 1

TOOL SETTINGS

Base material
- raw porcelain

Input for clay extrusion
- compressed air system system
- 140 psi: air pressure requirement

Toolpath kinematics execution by the robot
- PTP initial speed 45%
- LIN move initial speed 0.5 m/s
- Interpolation resolution 10 mm
- PTP toolpath definition

Tool making
1) build a material container using a pvc pipe
2) assemble the robot end-effector using metal and 3D printed components (FDM - PLA)
3) calibrate (set to zero) the end-effector positioning, in reference to the robot's 0,0,0 (xyz origin)
4) install the robot end-effector (nozzle diameter = 8 mm) on the robot head
5) connect the pvc pipe to the robot's end-effector through a flexible plastic hose (1500 mm long)

Software
- Robot end-effector 3D modeling: Rhinoceros V6
- Parameterization of the end-effector geometry: Grasshopper
- Generation of the robot toolpath: Kuka Prc

RESULT: NEGATIVE

The failure of TEST 1 is due to several factors.

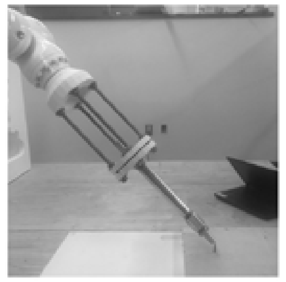
PVC PIPE
- the air under pressure accumulates in the pipe
- the base material exceeds air bubbles
- the pvc pipe used is not suitable for air pressure: it blew up shortly after the test started

PLASTIC HOSE
- the inner texture produces friction that stops the material flow towards the nozzle

NOZZLE
- 8 mm diameter is excessive, the material doesn't flow consistently


compressed air system


kuka 6 axis robot


robot end-effector


plastic hose

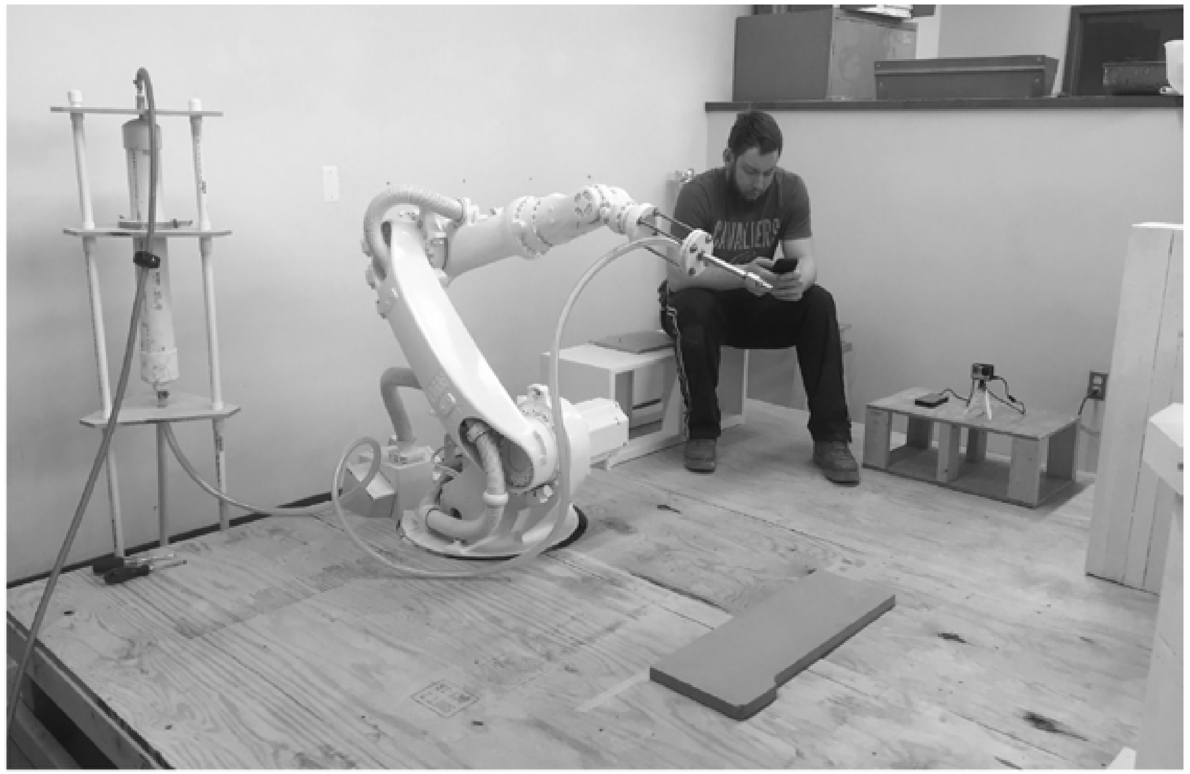

PVC pipe

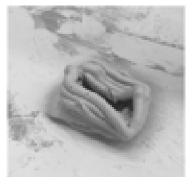
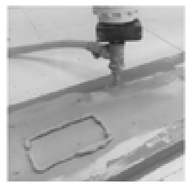

interchangeable nozzles

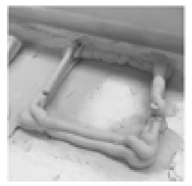
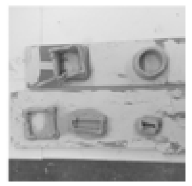

base material - porcelain


example of utcome

OUTCOME



TEST 2

TOOL SETTINGS

Base material
- raw porcelain

Input for clay extrusion
- compressed air system system
- 140 psi: air pressure requirement

Toolpath kinematics execution by the robot
- PTP initial speed 45%
- LIN move initial speed 0.5 m/s
- Interpolation resolution 10 mm
- PTP and LIN toolpath definition

Tool making
1) build a material container using a clear pvc pipe suitable for compression
2) install a piston that pushes and retracts based on different inputs (using compressed air)
3) assemble a simplified end-effector using metal components and 3D printed parts (FDM - PLA)
4) install the nozzle (diameter = 4/6 mm) on the robot head
5) connect the pipe to the robot end-effector through a flexible and not inner-textured hose (1000 mm long)

Software
- Robot end-effector 3D modeling: Rhinoceros V6
- Parameterization of the end-effector geometry: Grasshopper
- Generation of the robot toolpath: Kuka Prc

RESULT: NEGATIVE

The failure of TEST 2 is due to several factors.

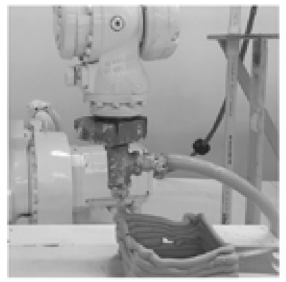
PVC PIPE
- the pvc pipe used is too long: the piston doesn't push all the way through
- the refilling process takes too long, it's hard to control the material consistency
- if the porcelain is too dense, the air gets compressed in the pipe and the system doesn't allow to release it

HOSE
- the hose used is too long, it contains too much clay (by the time the porcelain gets to the end-effector, a new refill is needed)
- it is difficult to clean the plastic hose at the end of the process


compressed air system


kuka 6 axis robot


robot end-effector


plastic hose


clear PVC pipe


interchangeable nozzles

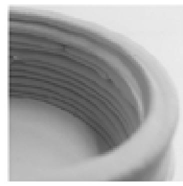

base material - porcelain


example of outcome

OUTCOME





TEST 3

TOOL SETTINGS

Base material
- raw porcelain

Input for clay extrusion
- mechanical input

Toolpath kinematics execution by the robot
- PTP initial speed 100%
- LIN move initial speed 2 m/s
- Interpolation resolution 10 mm
- LIN toolpath definition

Tool making
1) build a screw-pump mechanism out of welded metal components
2) fit an auger drill bit inside a tubular
3) cut the tubular and insert a funnel which is the material filler
4) connect the tubular to a nozzle
5) attach the nozzle to a flexible hose (700 mm long) that goes into the robot end-effector (same of TEST2)
6) use a driller to induce the extrusion

Software
- Robot end-effector 3D modeling: Rhinoceros V6
- Parameterization of the end-effector geometry: Grasshopper
- Generation of the robot toolpath: Kuka Prc

RESULT: NEGATIVE

The failure of TEST 3 is due to several factors.

MECHANICAL SYSTEM
- the flow of material is too slow
- material consistency does not allow a constant flow
- a stepper motor is needed to provide more power

FILLER
- the system should be scaled-up for large scale applications: the funnel requires continuous refilling
- the filling procedure should be optimized by building a support structure

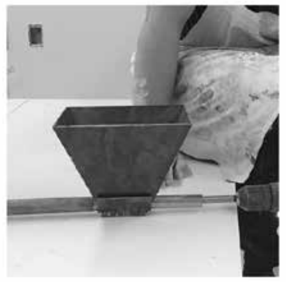

drill

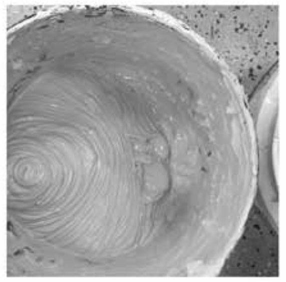

kuka 6 axis robot


robot end-effector


hose pipe-end-effector

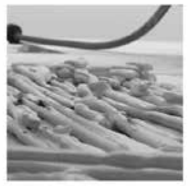

auger drill bit


filler


base material - clay


example of outcome

OUTCOME



TEST 4

TOOL SETTINGS

Base material
- raw porcelain

Input for clay extrusion
- mechanical input: stepper motor

Toolpath kinematics execution
- PTP initial speed 45%
- LIN move initial speed 0.5 m/s
- Interpolation resolution 5 mm
- LIN toolpath definition

Tool making
1) build an extruder based on open source 3D printed components (FDM - PLA)
2) assemble the 3D printed components with a clear pvc pipe
3) assemble a syringe to push the raw porcelain in the pipe
4) install a stepper motor on the extruder connected to Arduino microcontroller
5) connect the extruder to the robot end-effector (same of TEST 2-3, with a longer nozzle) using a flexible plastic hose (600 mm long)

Software
- Robot end-effector 3D modeling: Rhinoceros V6
- Parameterization of the end-effector geometry: Grasshopper
- Generation of the robot toolpath: Kuka Prc
- Programming of the stepper motor to control the extrusion flow: Ida-Arduino

RESULT: POSITIVE

The system is efficient enough for the experimental objectives. The material flows constantly accordingly with the extrusion pressure and the robot kinematics. However, technical optimizations are possible. Further iterations could improve the quality of the outcome. Some features that are suitable for improvements:

ADDITIVE MANUFACTURING LOD

- the robot programming allows the control of the layer thickness in the z direction. As the container is filled manually, the material is not uniformly compacted. For this reason it was difficult to manage the amount of porcelain extruded on the horizontal (xy) plane.

END-EFFECTOR

- the geometry of the end-effector could be optimized so that it might be used as an additional axis for the robot. For this purpose, a bigger stepper motor should be provided.

stepper motor

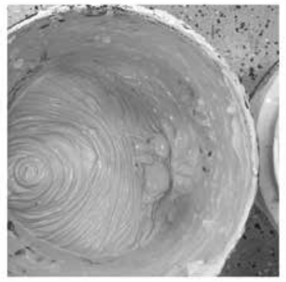
kuka 6 axis robot

clear PVC pipe

syringe

connector pipe-motor

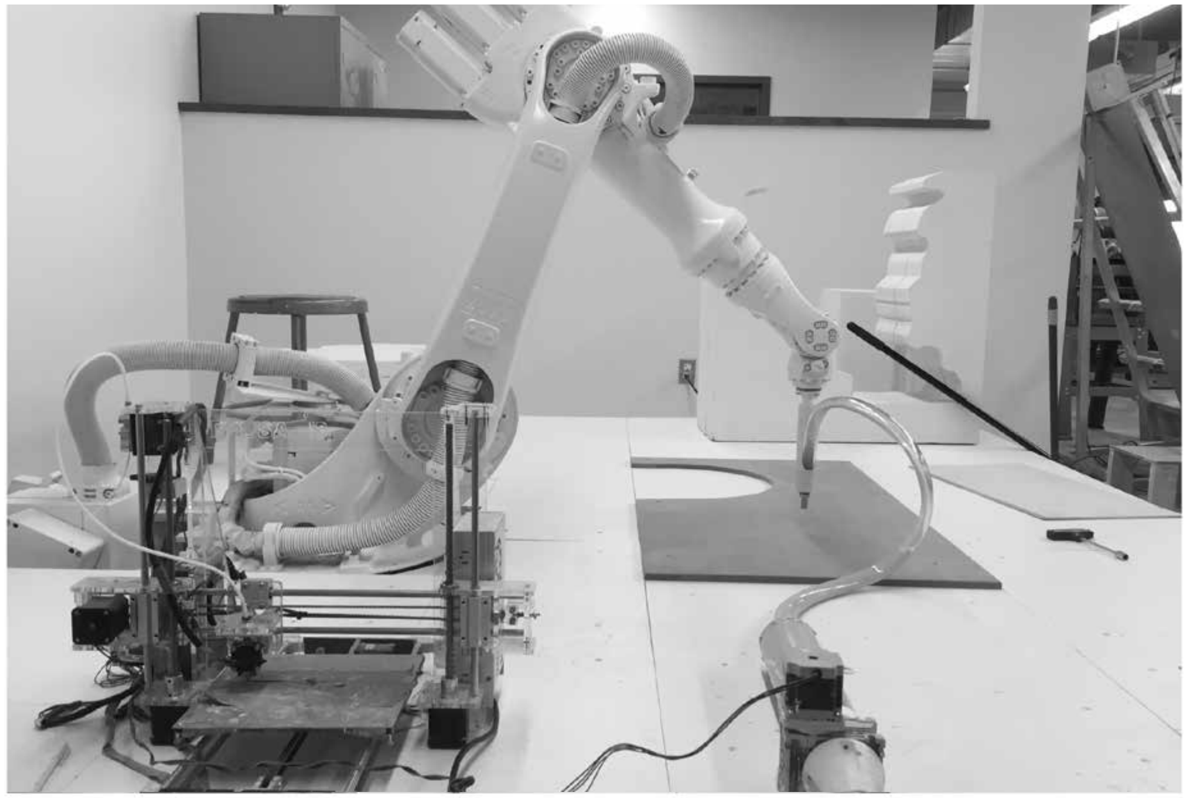
interchangeable nozzles

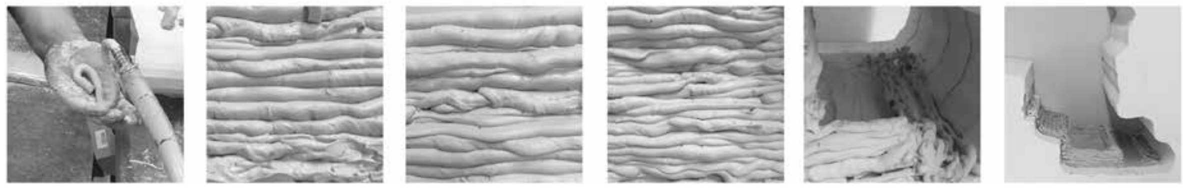


base material - porcelain

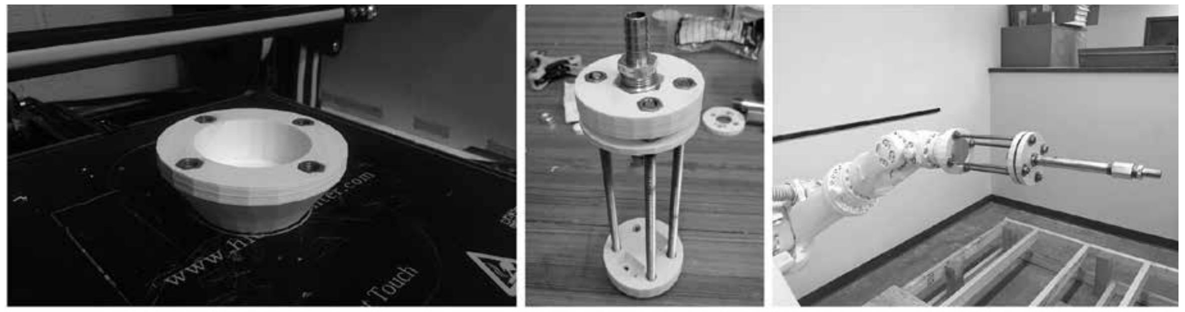
example of outcome

OUTCOME





END-EFFECTOR 1



DIGITAL FABRICATION ASSEMBLY INSTALLATION

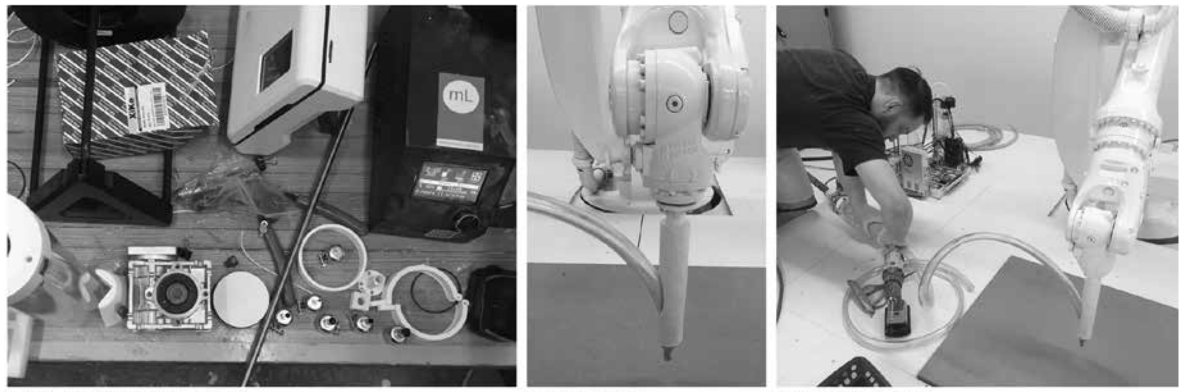
Fig. 7.22 Critical issues: the geometry of the end-effector has too many joints. It is not steady along z-axis while the robot is moving. For this reason it's difficult to calibrate the TCP (tool center point).

END-EFFECTOR 2-3

FABRICATION ASSEMBLY INSTALLATION

Fig. 7.23 Critical issues: the geometry of this end-effector is simpler. It is made of metal pieces and therefore more stable. However, it is too short. The robot head must be offset from the wall gap.

END-EFFECTOR 4



DIGITAL FABRICATION ASSEMBLY INSTALLATION

Fig. 7.24 Possible improvement: an extra axis (tool-A7) should be added to reach more points in the wall crack. A bigger stepper motor should be installed to improve the fluency of the material extruded.

	TEST 1	TEST 2	TEST 3	TEST 4
result	negative	negative	negative	positive
base material	raw porcelain	raw porcelain	raw porcelain	raw porcelain
material features	low shrinkage high viscosity	low shrinkage high viscosity	low shrinkage high viscosity	low shrinkage high viscosity
extrusion input	compressed air	compressed air	compressed air	compressed air
extrusion typology	cold	cold	cold	cold
extrusion features	140 psi	140 psi	driller	200 steps/rev
robot programming				
PTP initial speed	45%	45%	100%	45%
LIN initial speed	0,5 m/s	0,5 m/s	2 m/s	0,5 m/s
interpolation	10 mm	10 mm	10 mm	5 mm
toolpath	PTPmove	LINmove	LINmove	LINmove
execution mode	T1	T1	T1	AUTO
speed	10%	10%	10%	1-5 %
extruder				
container material	pvc pipe	clear pvc pipe	clear pvc pipe	clear pvc pipe
container diameter	150 mm	120 mm	funnel 160 x 200	120 mm
container length	900 mm	900 mm	180 mm	700 mm
filling method	manual	manual	manual	manual
connectors	pvc parts	pvc parts	pvc parts	pla AM parts
hose	textured	not textured	not textured	not textured
hose diameter	15 mm	15 mm	19 mm	19 mm
hose lenght	1500 mm	1000 mm	700 mm	600 mm
end-effector				
typology	test A	test B	test B	test C
axis	z (extension of A6)	z (extension of A6)	z (extension of A6)	z (extension of A6)
robohead connection	AM (PLA)	full steel	full steel	full steel
end-effector core	steel and AM (PLA)	stainless steel	stainless steel	AM (PLA)
total lenght	460 mm	120 mm	120 mm	240 mm
nozzle diameter	8 mm	4 mm	6 mm	4 mm
nozzle material	brass	brass	brass	brass
outcome				
progress	incomplete object	incomplete object	incomplete object	prototype
resolution	low	low	low	low
finishing	drying	drying	drying	drying
structural features	self supporting	self supporting	self supporting	self supporting
issues	PTP move is not the best option for AM	too many refills are needed - slow process	inconsistent flow of raw material	consistent flow but low precision
TRL	2-3	2-3	2-3	3-4

Phase 8: programming and virtual simulation

The robotic programming phase took place in the digital environment and operated with the robot's digital-twin[48] (Rosen et al., 2015). The process was divided into different stages: generation of the robot toolpath, conversion of toolpaths to robot code, and digital simulation of the script. The volume of the wall gap was 3D modelled and linked to a parametric digital environment,[49] to ease iterations and possible variations of the process. Then, the model was sliced into horizontal layers that were filled with an internal support geometry. The resulting polylines were broken into a list of targets for the robot to reach. The outline of each layer was taken and offset multiple times to generate the required wall thickness (Fig. 7.25).

Next, the robot toolpath was generated over the model. In order to do so, Kuka|Prc,[50] a plug-in that extends the software's capabilities and allows the remote programming of the robot axis was utilized (Fig. 7.26). This component was used to design a script (or algorithm) that converts target points into robot code and, simultaneously, activate the detection of collisions, reachability issues, and singularities. Before uploading the code in the robot controller, the axis kinematics were validated through simulations by visualising the robot at each of the targets (Fig. 7.27) and check for targets out of reach, joints out of range, singularity issues,[51] self-collisions, and collisions with surrounding objects (American National Standards Institute, 1999).

The virtual simulation provided an early opportunity to correct possible issues that may have occurred. A simulation of the robot kinematics in the physical world followed. Before interacting with the wall prototype, a basic script was provided to analyse if the robot could operate effectively within a simple geometrical constraints. The wall gap was approximated to a rectangular gap. This was an opportunity to check the positioning and the rotations of the nozzle at every target point (Fig. 7.28). In particular, the software simulations served to discern if the end-effector is just touching or colliding with the wall surface.

The programming was carried out in a Kuka | Prc software environment, a software designed in an academic context specifically to control robots produced by Kuka. The popularity of this software is

48 Digital-twin technology: https://www.forbes.com/sites/bernardmarr/2017/03/06/what-is-digital-twin-technolog y-and-why-is-it-so-important/.

49 The digital model was linked to Grasshopper: This plug-in is beneficial for developing surface patterning and textures, when the designers need to iterate quickly through many variations.

50 KukaPrc calculates each position statically, ignoring the targets before and after the current one. By contrast, the actual robot controller calculates the next position dynamically based on the current position. For a rigorous simulation of these, we added targets through interpolation.

51 The American National Standard for Industrial Robots and Robot Systems defines singularities as "a condition caused by the collinear alignment of two or more robot axes resulting in unpredictable robot motion and velocities". Therefore, the three types of singularities are defined by which joint alignments cause the problem: "wrist", "shoulder", and "elbow" singularities. See: https://www.robotics.org/. A visual example of a six-axis robot singularities con be checked out at: https://vimeo.com/20095999.

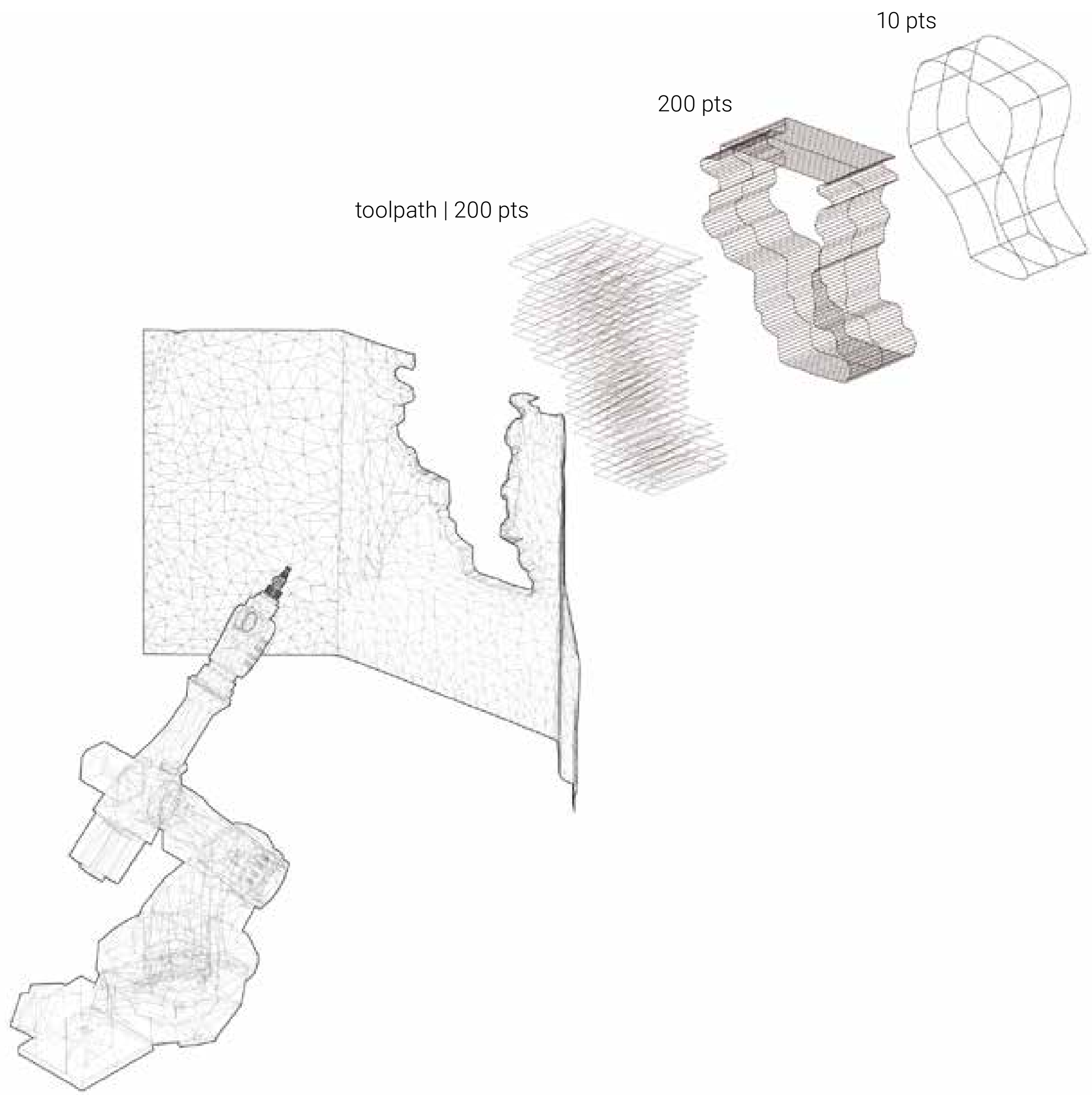


Fig. 7.25 Schematic axonometric visualization of the robotic toolpath. Profile of the gap reconstructed with interpolation of points detected in physical space.

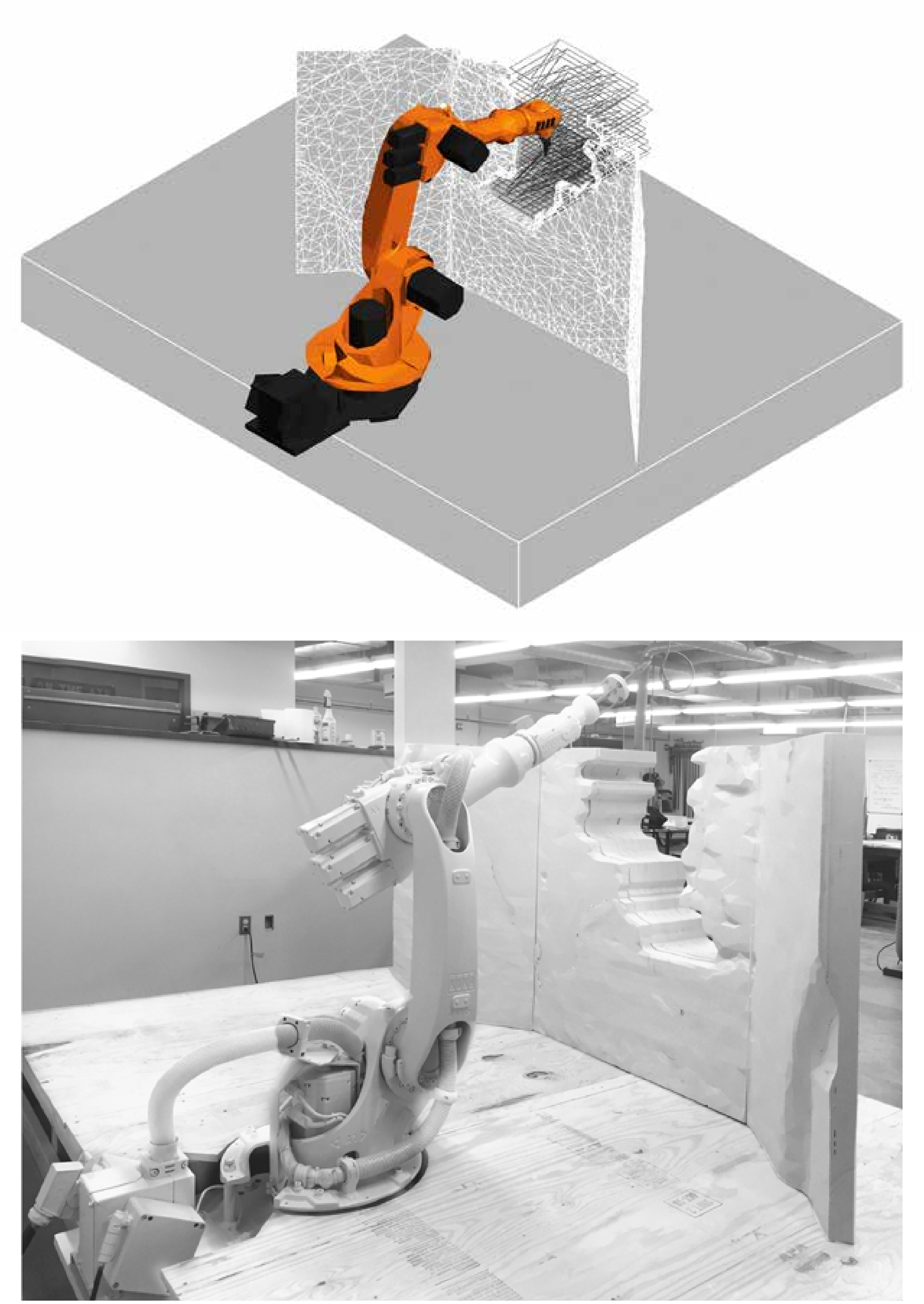


Fig. 7.26 Digital simulation of the robot work cell (digital-twin) in Kuka|Prc and experimental set up in the physical world.

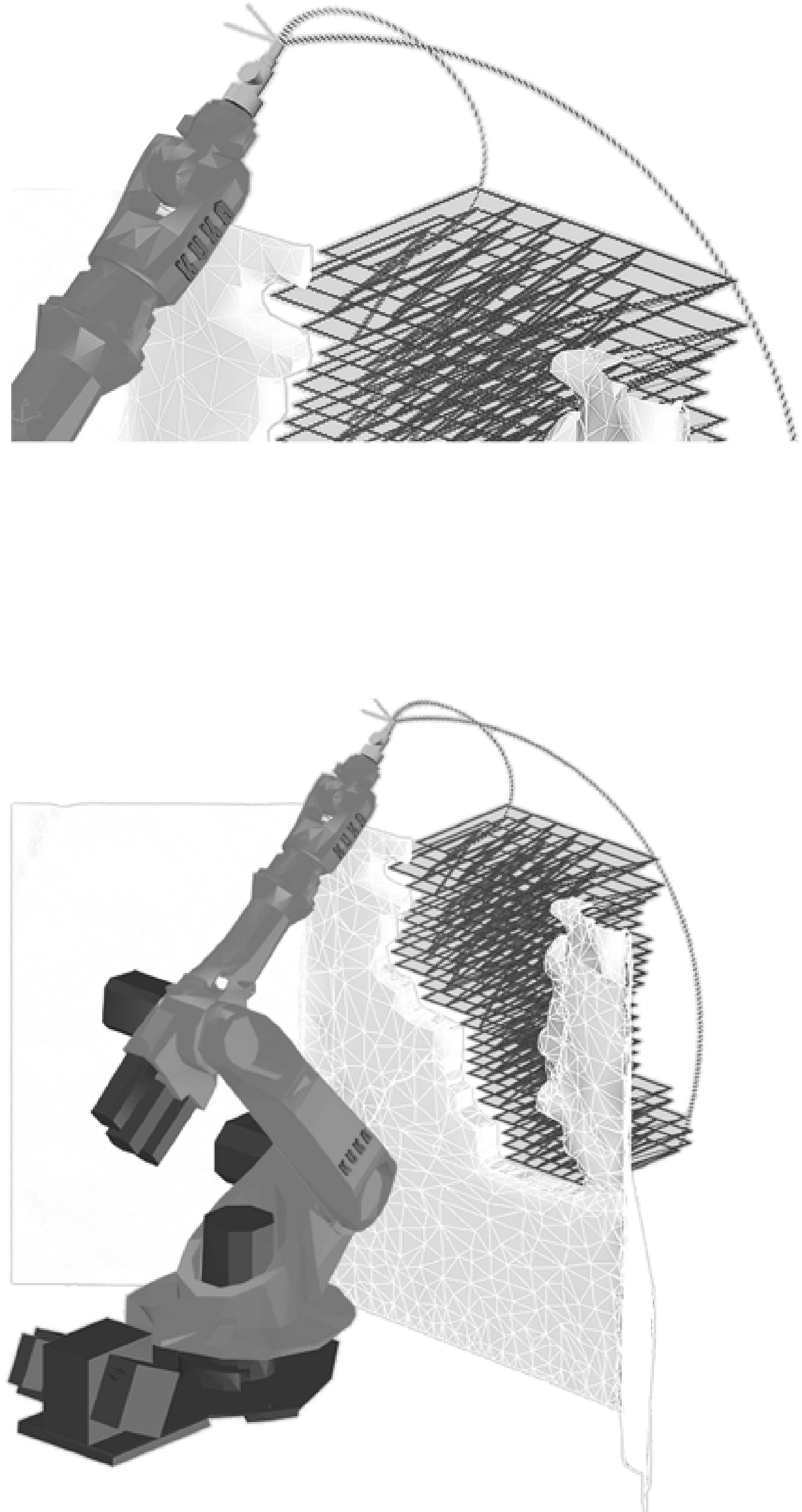


Fig. 7.27 Virtual simulation of the robot kinematics and digital visualization of the toolpath within the wall gap. The top image shows a detail of the toolpath for ALM.

given by the fact that it is designed to be used by architects familiar with algorithmic design interfaces (Braumann and Cokcan, 2012). Access to knowledge, however, to date is not structured in a global way, neither at the level of academic teaching nor of manuals. The experiment has required active participation within the Robots in Architecture[52] community, where architects without programming backgrounds share their projects trying to solve common technical projects. Frequent contact with the developer himself[53] was not necessary to respond in a customized and timely manner to the needs that emerged during this experimental phase.

52 Robots in Architecture forum. https://forum.robotsinarchitecture.org/.

53 Johannes Braumann: https://iaac.net/dt-team/johannes-braumann/.

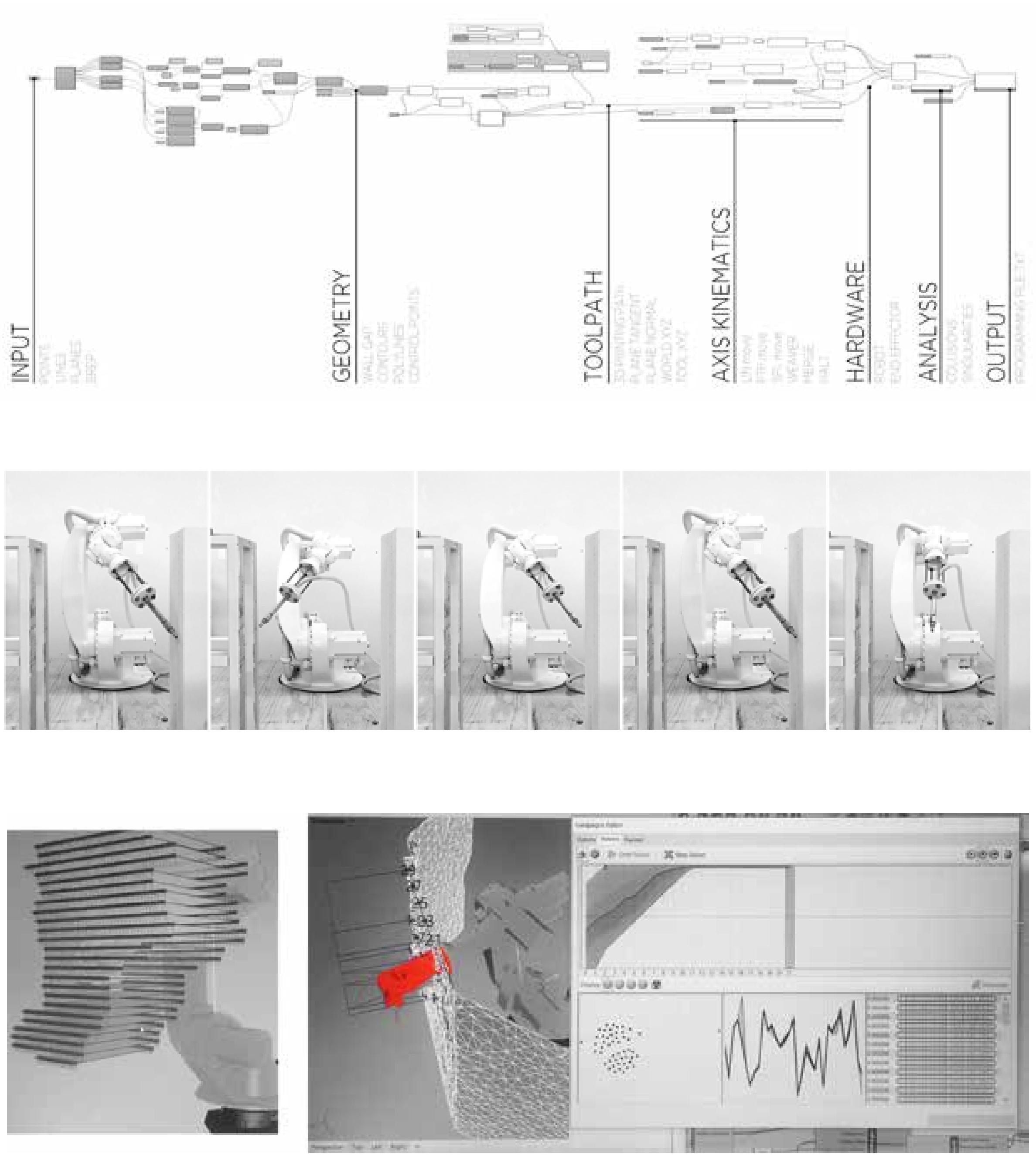


Fig. 7.28 Above: construction of the algorithm for the geometric definition of the toolpath and for the control of the robot kinematics. The input of the algorithm is given by the digital model of the wall damaged with the gap. The geometry of the gap is then divided into layers consisting of control points that are registered as targets to be reached in space. The resulting linear path is converted to a robotic toolpath that is executed by the end-effector (hardware). The script output is defined by lines of code, expressed rotations of each axis with respect to the initial "master" position set as "zero". Center: frames taken during a first test run of a simplified script in which the robot executes a toolpath within regular geometric limits: the shape of the gap has been simplified to a parallelepiped. Below: virtual simulation of the robot toolpath (on the left) and identification of the singularities in the execution of the movements (in the center). To optimize script generation, the Galapagos Grasshopper component (on the right) was used, which allows you to set the minimum and maximum limits of a function. In this case, Galapagos was used to reduce the maximum range of axis rotations, minimizing the occurrence of kinematic arrangements beyond hardware limits.

Phase 9: setting to zero the wall mockup

Procedure 1

Objective

- this is a simulation of a on-site geometrical survey using a robot

Equipment (Fig. 7.29)

- Kuka robot [controlled with the Teach Pendant]
- sharp end-effector
- KukaPrc and Rhinoceros V6

Methodology

1) define a sharp end-effector. The tip should be suitable to take down coordinates of specific point in the physical space;
2) use the end-effector to reach points on the outline of the wall crack;
3) use the Teach Pendant to record control points. OPTION 1: Work on the YZ Cartesian plane. OPTION 2: Work on the three-dimensional space; collect coordinates to elaborate a script (LIN move); export the script; import the script in Grasshopper; use the coordinates to build a parametric 3D model of the crack; define the robot's toolpath accordingly. Iterations: 20 scripts have been created. 10 referenced points have been added at every iteration (Fig. 7.31).

Procedure 2

Objective

- check the reachability of points in the physical space within the robot's workcell

Equipment (Fig. 7.30)

- Kuka robot, programmed in KukaPrc
- laser level

Methodology

1) define the robot toolpath in KukaPrc with set intervals between each movement; 2) upload the script in the teach pendant; 3) install the laser level on the robot's head; 4) run the script a) HORIZONTAL LIN movements b) VERTICAL LIN movements; 5) take a picture of every LIN movement; 6) overlap the pictures to obtain a laser grid; 7) check if every point of the wall prototype is reachable (Fig. 7.32, Fig. 7.33).

Robot settings

- AUTO mode;
- speed 3%;
- pause command 2 sec.

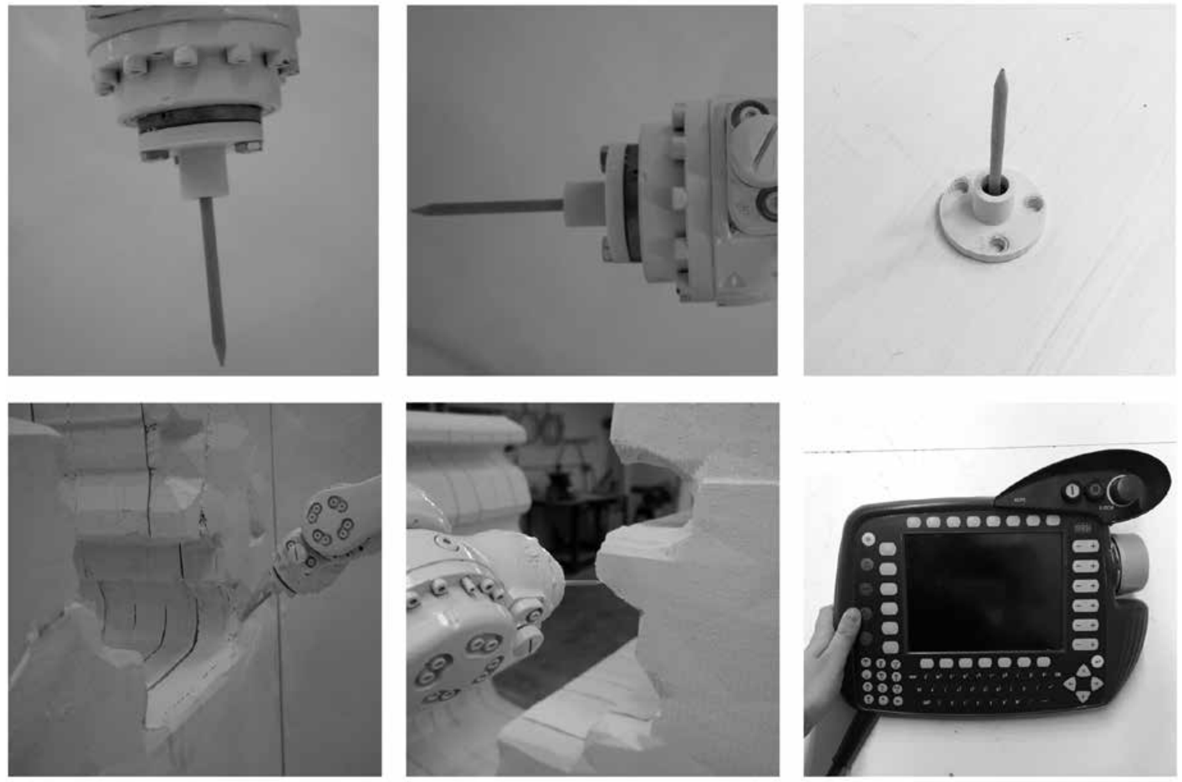
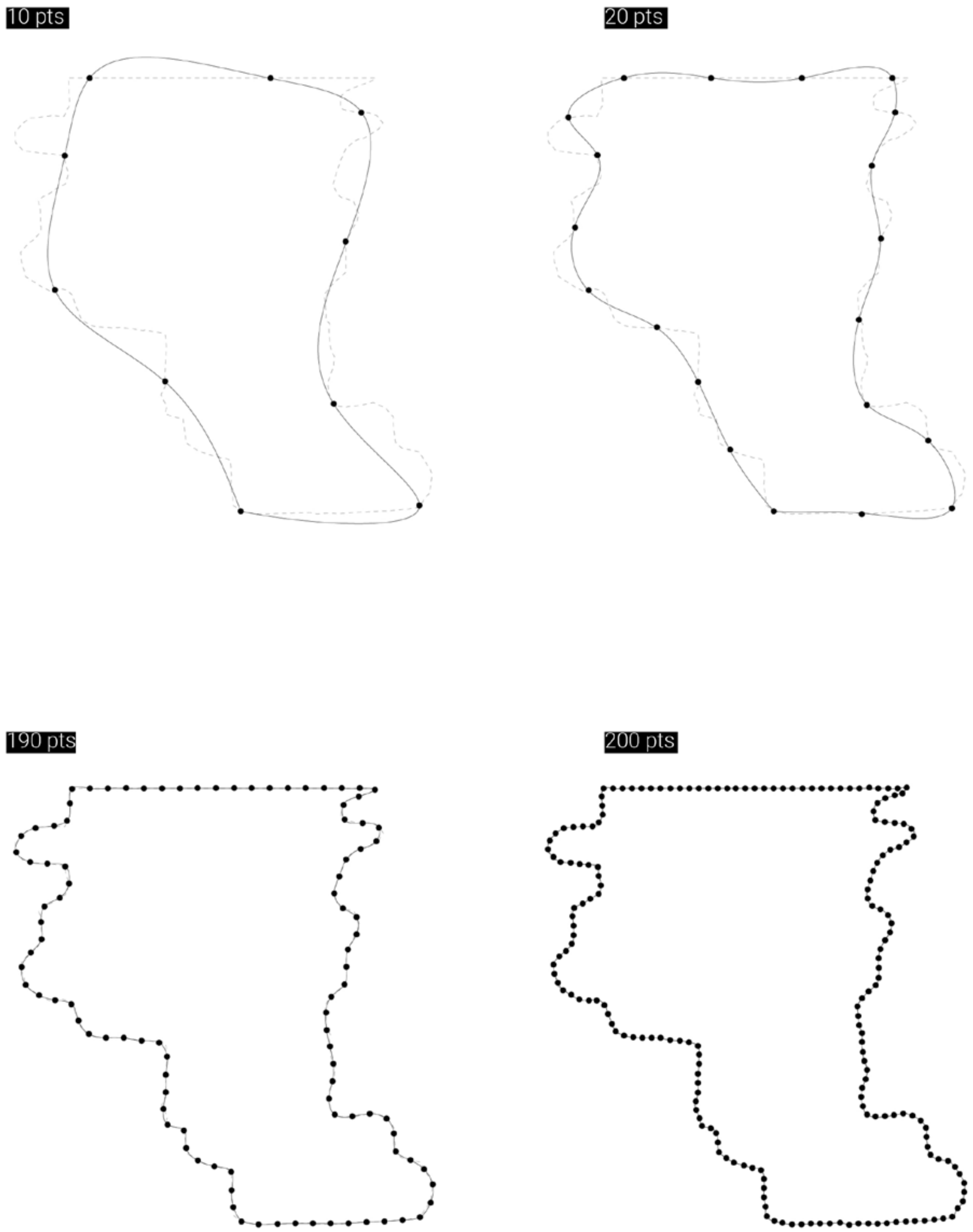


Fig. 7.29 End-effector used to record the target point coordinates in the physical world.The data was transferred into the software after export from the Teach Pendant.
Fig. 7.30 Laser level installed on the robot head. This approach recalls the possible use of robots for building surveys.



PT.1	{E6POS:	X	692.256,	Y	-69.637,	Z	652.797,	A	165.006,	B	26.457,	C	-6.798,	E1	0,	E2	0,	E3	0,	E4	0}
PT.2	{E6POS:	X	824.705,	Y	-60.107,	Z	687.244,	A	175.458,	B	9.583,	C	-0.755,	E1	0,	E2	0,	E3	0,	E4	0}
PT.3	{E6POS:	X	878.251,	Y	-71.701,	Z	645.335,	A	-171.837,	B	0.292,	C	89.985,	E1	0,	E2	0,	E3	0,	E4	0}
PT.4	{E6POS:	X	941.502,	Y	-78.374,	Z	621.215,	A	-156.794,	B	-5.555,	C	90,	E1	0,	E2	0,	E3	0,	E4	0}
PT.5	{E6POS:	X	1010.097,	Y	-74.951,	Z	633.588,	A	-150.333,	B	-9.491,	C	89.977,	E1	0,	E2	0,	E3	0,	E4	0}
PT.6	{E6POS:	X	1072.445,	Y	-66.526,	Z	664.04,	A	-165.227,	B	-12.108,	C	89.975,	E1	0,	E2	0,	E3	0,	E4	0}
PT.7	{E6POS:	X	1126.307,	Y	-54.577,	Z	707.231,	A	-177.432,	B	-11.355,	C	-0.526,	E1	0,	E2	0,	E3	0,	E4	0}
PT.8	{E6POS:	X	1178.669,	Y	-42.145,	Z	752.167,	A	175.607,	B	-12.611,	C	0.94,	E1	0,	E2	0,	E3	0,	E4	0}
PT.9	{E6POS:	X	1236.019,	Y	-31.43,	Z	790.898,	A	176.377,	B	-12.802,	C	0.823,	E1	0,	E2	0,	E3	0,	E4	0}
PT.10	{E6POS:	X	1301.118,	Y	-24.682,	Z	815.288,	A	177.107,	B	-5.561,	C	0.288,	E1	0,	E2	0,	E3	0,	E4	0}

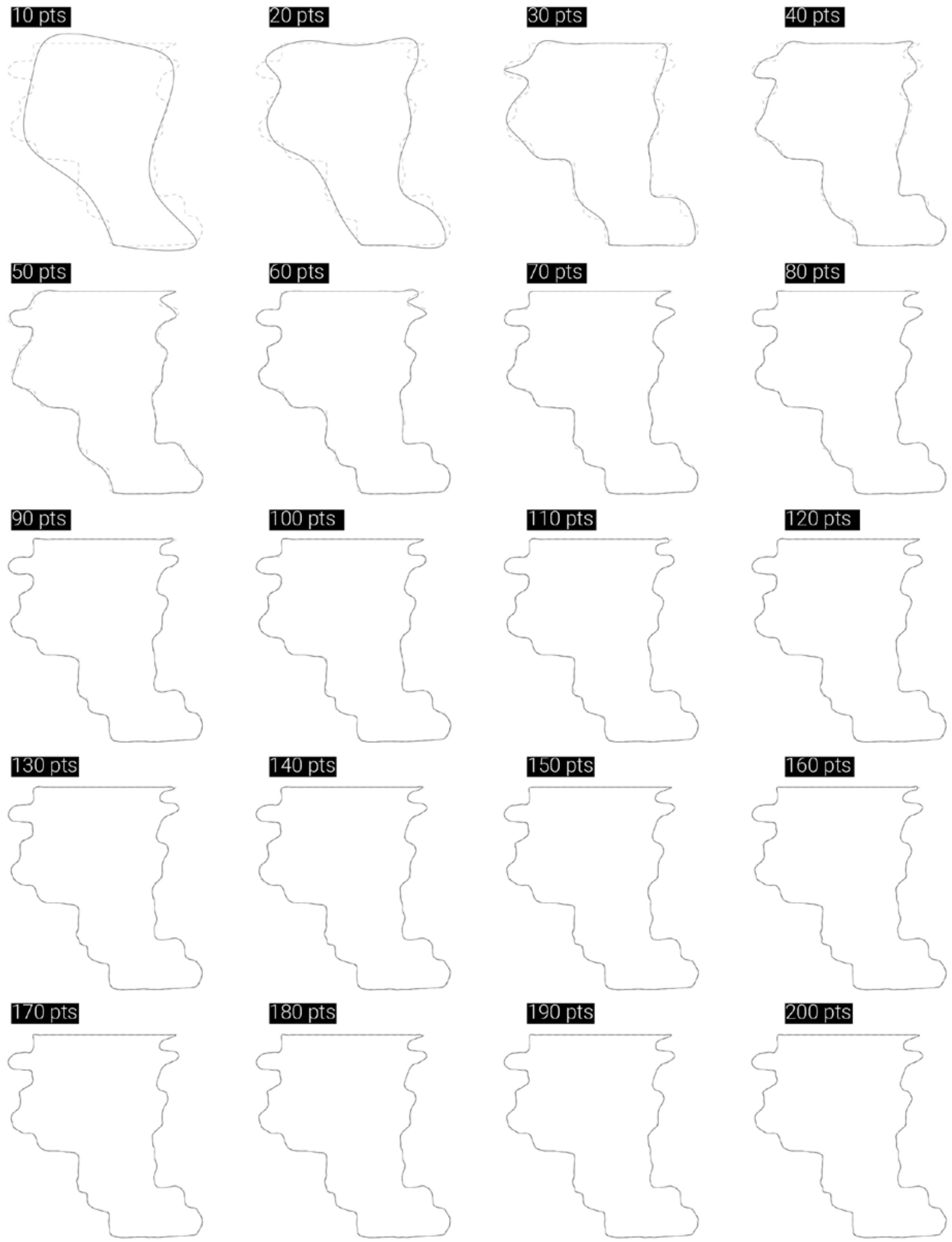
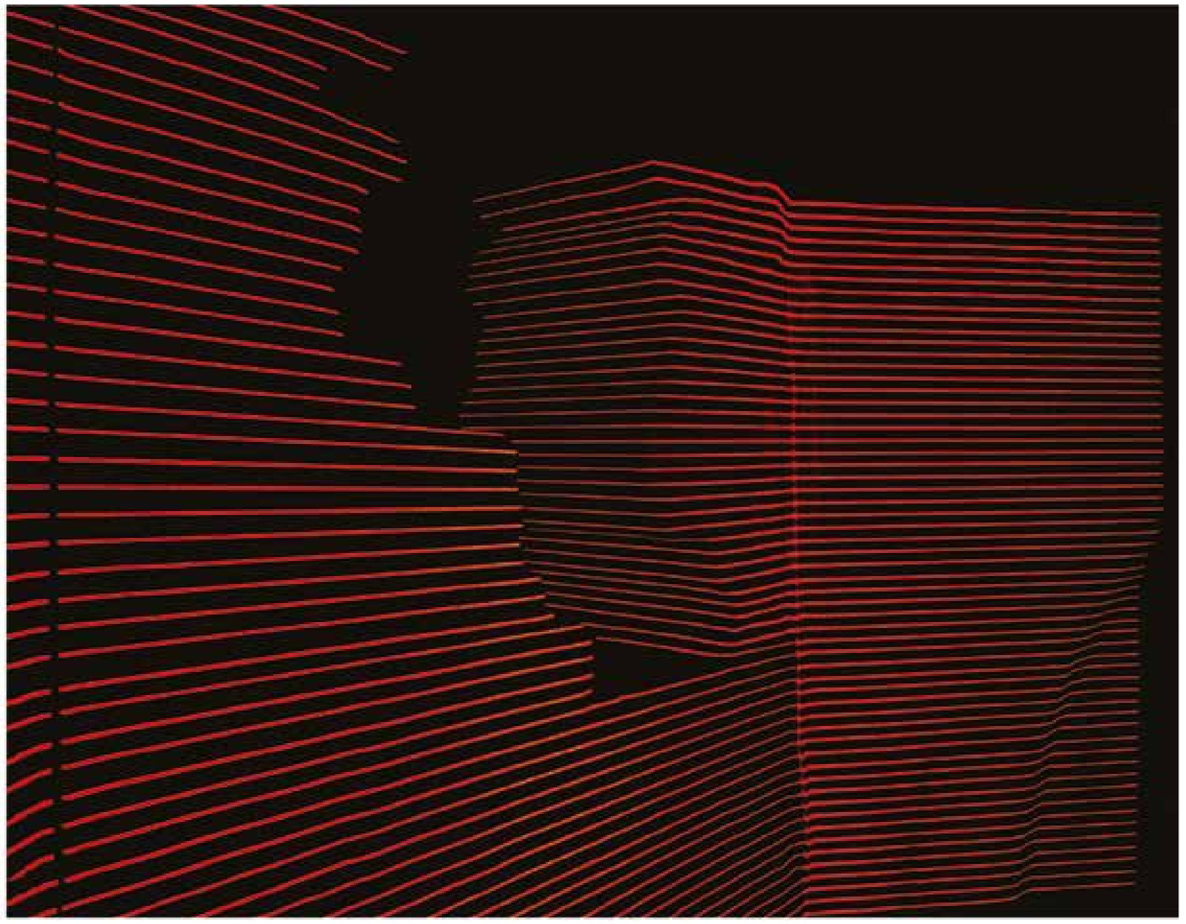


Fig. 7.31 Different interpolations based of the input of the data collected during the motion of the robot around the perimeter of the wall gap.



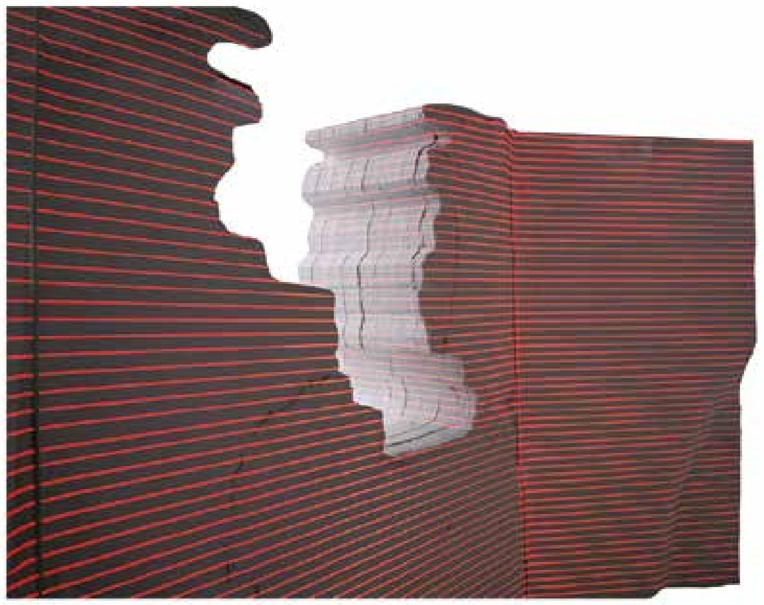
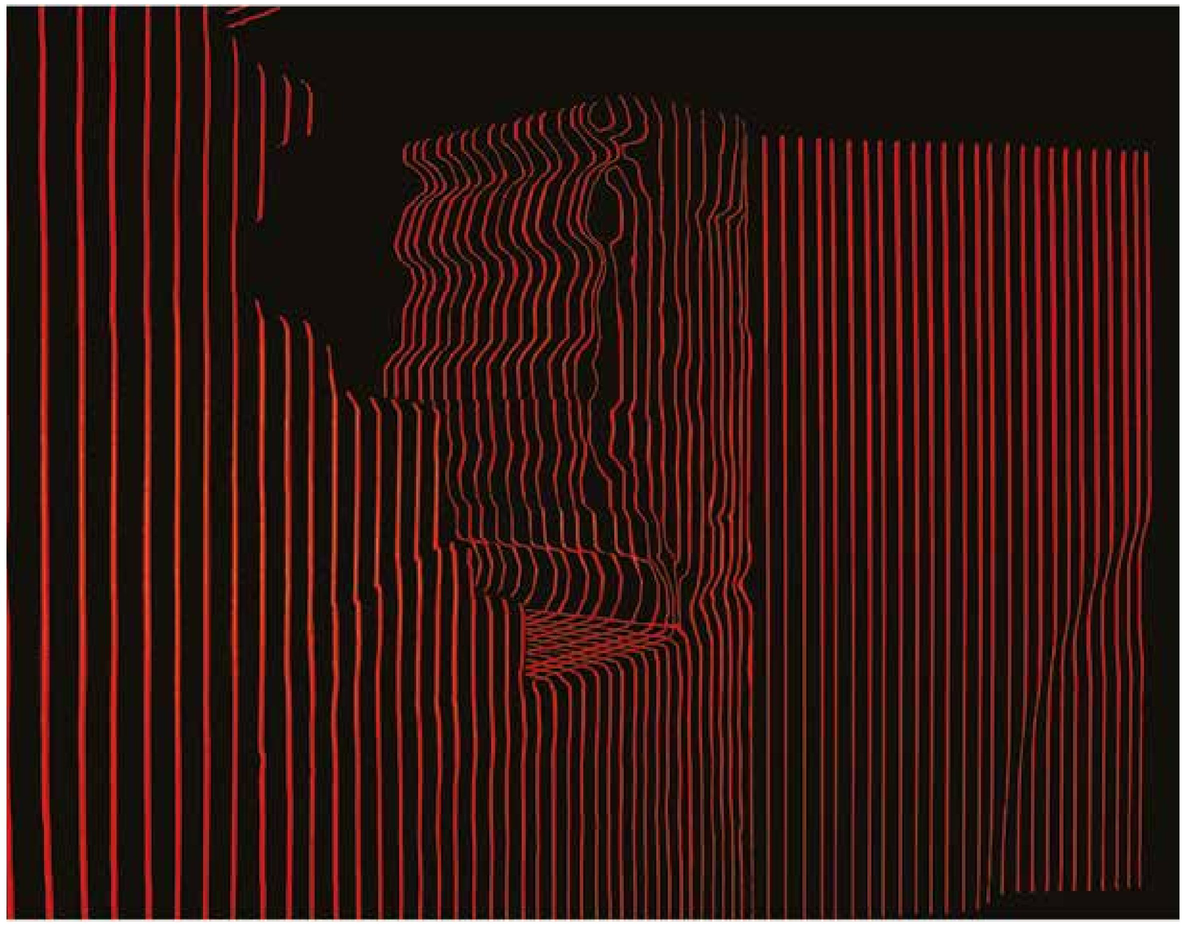


Fig. 7.32 Laser light pattern on the wall prototype. Horizontal lighting realized through vertical toolpath divided into regular intervals.



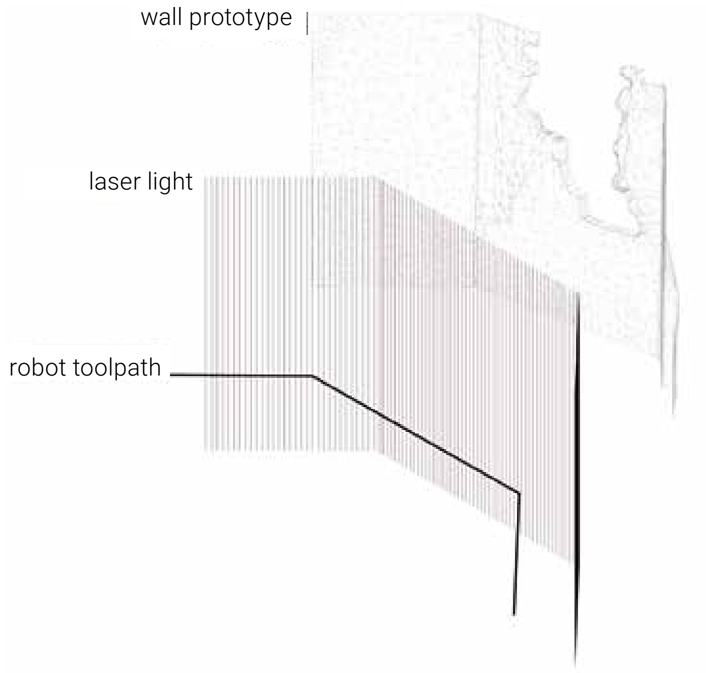


Fig. 7.33 Laser light pattern on the wall prototype. Vertical lighting realized through horizontal toolpath divided into regular intervals. The toolpath is programmed to pauses every 2 cm.

Phase 10: physical outcome defined by filling a wall gap through off-site, robotic, ceramic-based additive manufacturing

"As the millennium came to a close, many agreed that a technical revolution was in the making, and that architecture and urbanism would be prominently affected by it [Mario Carpo, 1994]

The quantitative data collected during the survey of the Woodward Avenue Church were turned into matter through the full-scale realization of a partial wall. This wall prototype is a test-bed to simulate possible on-site operations of additive manufacturing for the production of large-scale architectural elements on complex geometrical constraints such as wall gaps. Specific equipment for testing the digital manufacturing process was provided. A six-axis robot was used to accomplish the kinematic sequences. Installed on the robot head is an end-effector (a nozzle connected to a flexible hose) for the extrusion of the printing material. A pipe was used to push the printing material, by a compressed air system, into the end-effector. Clay was chosen as a base material for the experiment because it is easily recyclable, comparatively inexpensive, and able to be worked to achieve a high-quality finish.

The robot code was used to simulate and validate the robot movements (Fig. 7.34). After being verified through simulation, the robot code could be uploaded to the robot controller. Then the code was loaded into the robot controller and it was run at reduced speed, with no work piece and with the extrusion head disabled. Once the kinematics were verified, the additive manufacturing process was tested. The responsiveness of the material (viscosity, hardening rapidity, and compressive strength limitation) was a key point in relation to the different surface slopes deposited through the extruder. During the experimental phases, certain aspects were monitored. They were worthy of being investigated to evaluate precision, replicability, and measurability of the performance.

The experiments and measurements were carried out in the laboratory given the access to available robotic equipment. The LTU industrial robot is structured in such a way that the workcell is static - a common set up for most academic robotic workcells. This means that a dynamic support system would be needed to use such a machine on-site. Additionally, an array of sensors would be required for the immediate return of the geometric limits defined by the intervention site and by any pre-existing elements. Components of this type are attributable for example to the Digital Construction Platform,[54] a mobile system capable of on-site design, sensing, and fabrication of large-scale structures that combines a large hydraulic boom arm and a smaller electric 5-axis robotic arm (Keating et al., 2014).

The technical structure made it possible to have a work platform and production of customized technological units that could be made directly in situ or manufactured and assembled on-site. A project prior to this which aimed to investigate the same operating methods is the Pike Loop,[55] a 22m long structure built from bricks. It was built in situ with an industrial robot from a movable truck trailer.

54 Digital Construction Platform at MIT Media Lab: https://vimeo.com/247270007.

55 Pike Loop project at ETH Zurich: http://www.gramaziokohler.com/web/e/projekte/159.html.

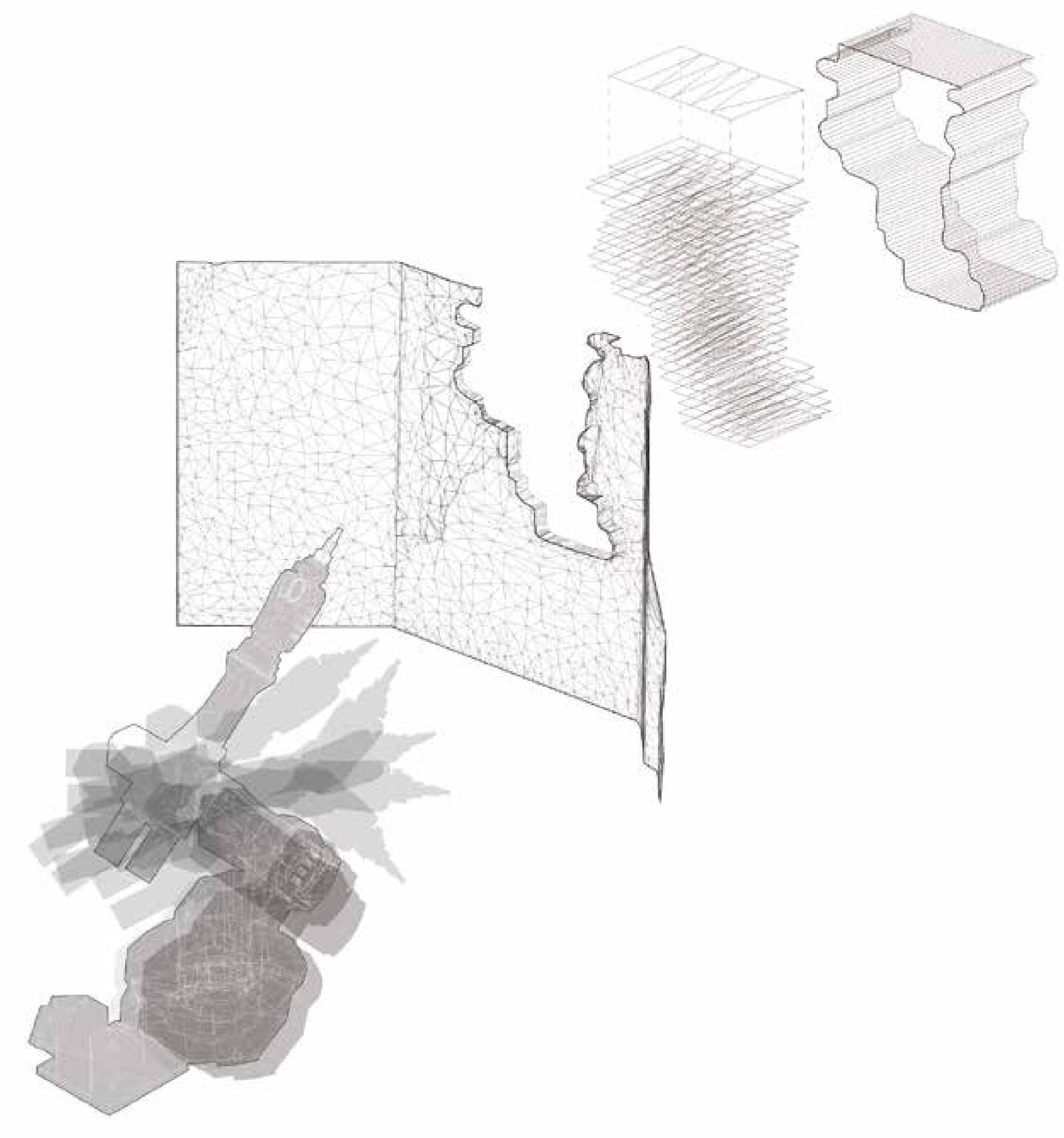


Fig. 7.34 Axonometric and diagrammatic representation of: kinematics of the robot - laboratory prototype of the pre-existing damaged walls defined by the surface mesh detected in situ - toolpath of the robot defined by perimeter extrusion and internal support layers - volumetric geometric configuration of the masonry gap. This scheme represents the ideal scheme of development, with the gap extruded in all its target points and with the use of an end-effector able to minimize collisions between the robot and the volume of the existing architectural wall gap.

The digitally designed brick structure was further articulated by a weighted compressing and tensioning of the brick bond (Bärtschi et al., 2010). The realization in situ would therefore require the setting up of an ad hoc research project. In this case it would be worth considering the use of cable-robots, that is machines able to operate in three-dimensional space and connected through cables to a decentralized control core. These systems are being studied in the main international research centers on robotics. The intensification of research in this field during the last decade was based on the 'robot boom' in the general manufacturing industry that took place in Japan in the 1970s.

The adoption of robots was a logical approach for Japanese construction firms. The single-task construction robots that were subsequently developed. The initial focus was on simple systems that could execute a single, specific construction task in a repetitive manner[56] (Bock and Langenberg, 2014). The operation of single-task robots,[57] which started the development of the so-called integrated automated construction sites, was used as a reference for several projects recently studied in the academic field. Among these, the Mini-builders project[58] is mentioned, developed at the IAAC - Institute for Advanced Architecture of Catalonia. The approach to digital fabrication, robot-oriented construction (Figliola, 2019), is defined by the use of small robots directly in situ. They are programmed to work in a coordinated manner and can be specialized independently for the production through additive manufacturing of vertical or horizontal partitions for small architectural technological systems. A further example is given by the On-Site Robotics research[59] which saw the creation of a prototype by using a cable-robot in situ equipped with a nozzle to extrude fluid-dense materials. Given the simplicity of the production and robot, this process can be scaled dynamically and deploy both horizontally and vertically.

This experiment made use of an autonomous drone remotely driven, only during the phase of quantitative geometric survey. However, the use of these systems for the supply of technological components on-site or for monitoring the manufacturing process is not excluded. The Flying Assembled Architecture project[60] in this speculative context, was a pioneer in 2011 of a concept test that employed a multitude of single-task quadrotor helicopters for the assembly of an architectural installation. The flying vehicles collaborated according to mathematical algorithms that translate

56 The capability of a robot to execute simple and single tasks meets the description of Capek automated machines, in the sci-fi PLAY R.U.R. - Rossumovi Univerzální Roboti (Rossum's Universal Robots). It marks the first use in 1921 of the word "robot" to describe an artificial person.
57 Rather than merely shifting complexity from the construction site into a structured prefabrication environment, the deployed single-task robotic systems could be used locally on-site for: demolition, surveying, excavation, paving, tunnelling, concrete transportation and distribution, concrete slab seeding and finishing, welding and positioning of structural steel members, fire-resistance and paint spraying, inspection, and maintenance.
58 Mini-builders project: https://robots.iaac.net/. Further information at: https://vimeo.com/97976677.
59 On-Site Robotics ai IAAC Barcelona: https://iaac.net/project/on-site-robotics/. Further information available at: https://vimeo.com/300525287.
60 Flight Assembled Architecture at ETH Zurich: http://gramazio-kohler.arch.ethz.ch/web/e/projekte/209.html.

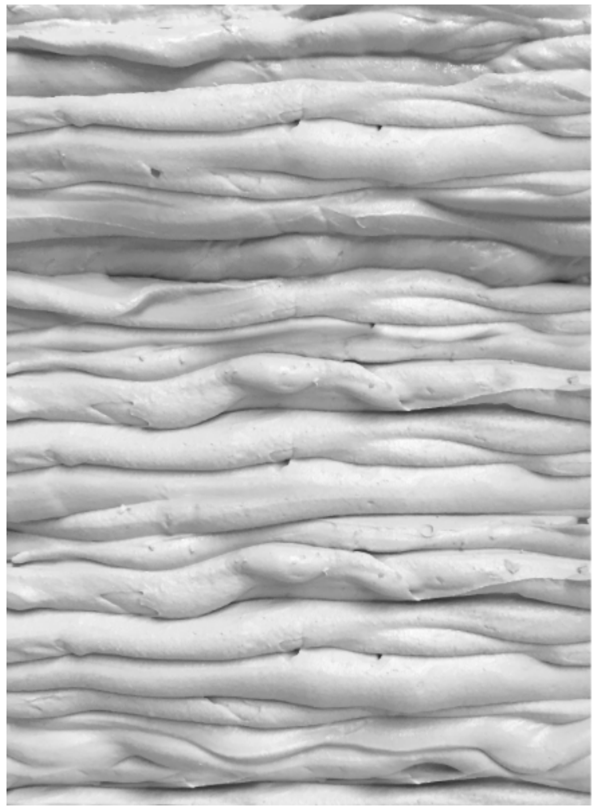


Fig. 7.35 Above: manual filling of the tube containing the extrusion material. This process can be improved by using mechanical systems for filling that prevent the formation of air bubbles in the liquid-viscous mixture. Below: resolution of the extruded layers that define the volume of the gap. The presence of inaccuracies and air bubbles can be improved and depends partly on how the container is filled.

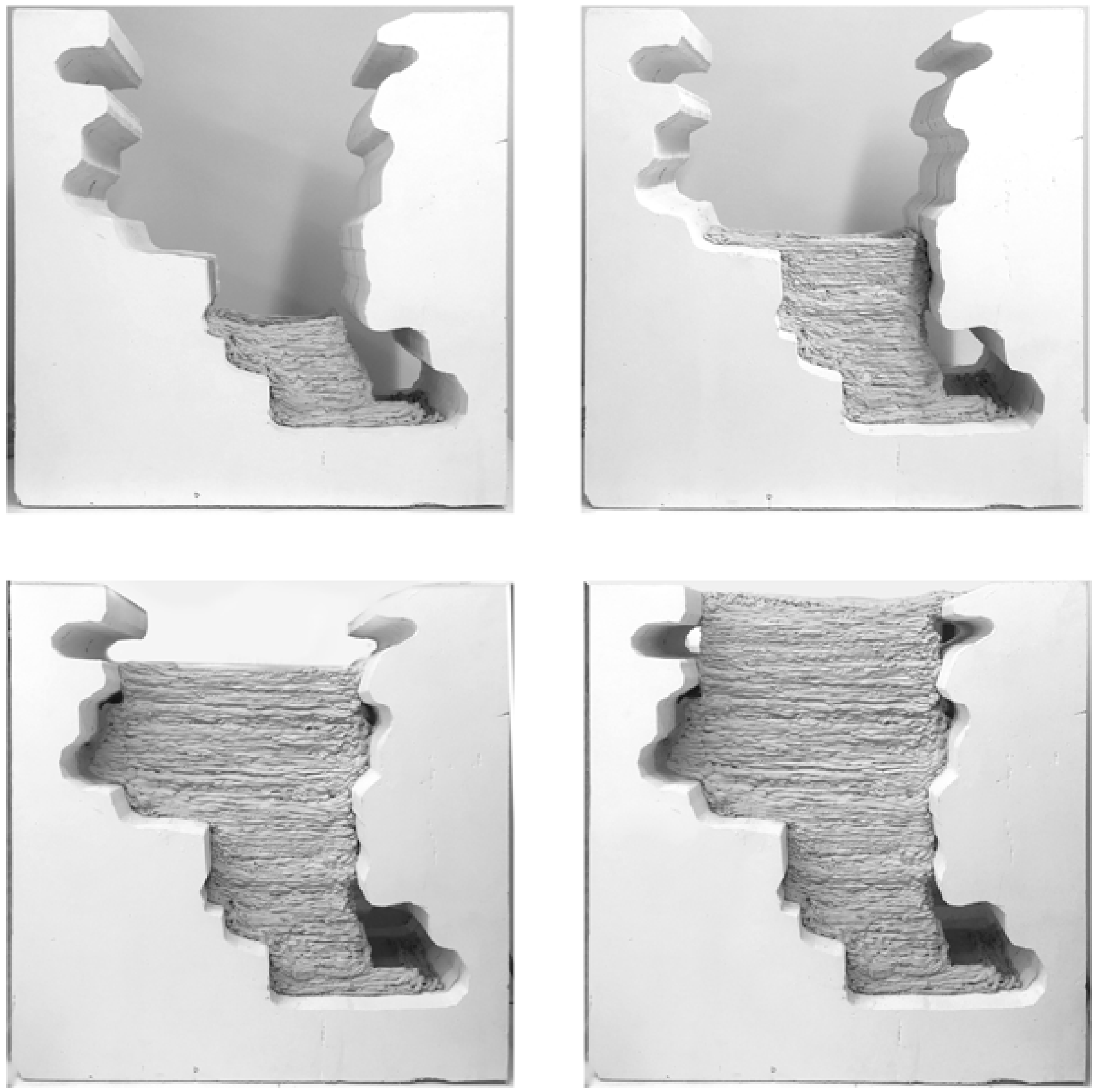


Fig. 7.36 Construction phases of the masonry gap through large-scale robotic additive layer manufacturing. The extrusion process needed to be divided into four sessions, ie the volume was created in four days. This four day process allowed the material to dry during the night and not collapse under the weight of the subsequent layers. Moreover, the script generated by the digital algorithm containing the robot's toolpath has been exported in two parts, due to the limit of the robot software to be able to read files that do not contain more than 703 lines of code, including within a disk space of 65 Kb. Circumstantial conditions such as: budget, timeframe for setting up the experiment, material availability of the people involved in this research and laboratory tools have meant that the first implementation test resulted in the final outcome. However, all the improvements and technical optimisations that can be made in a possible future development will be taken into consideration, to improve the print resolution and the effectiveness of the end-effector to reach all the target points defined within the project objective in the simulation phase digital.

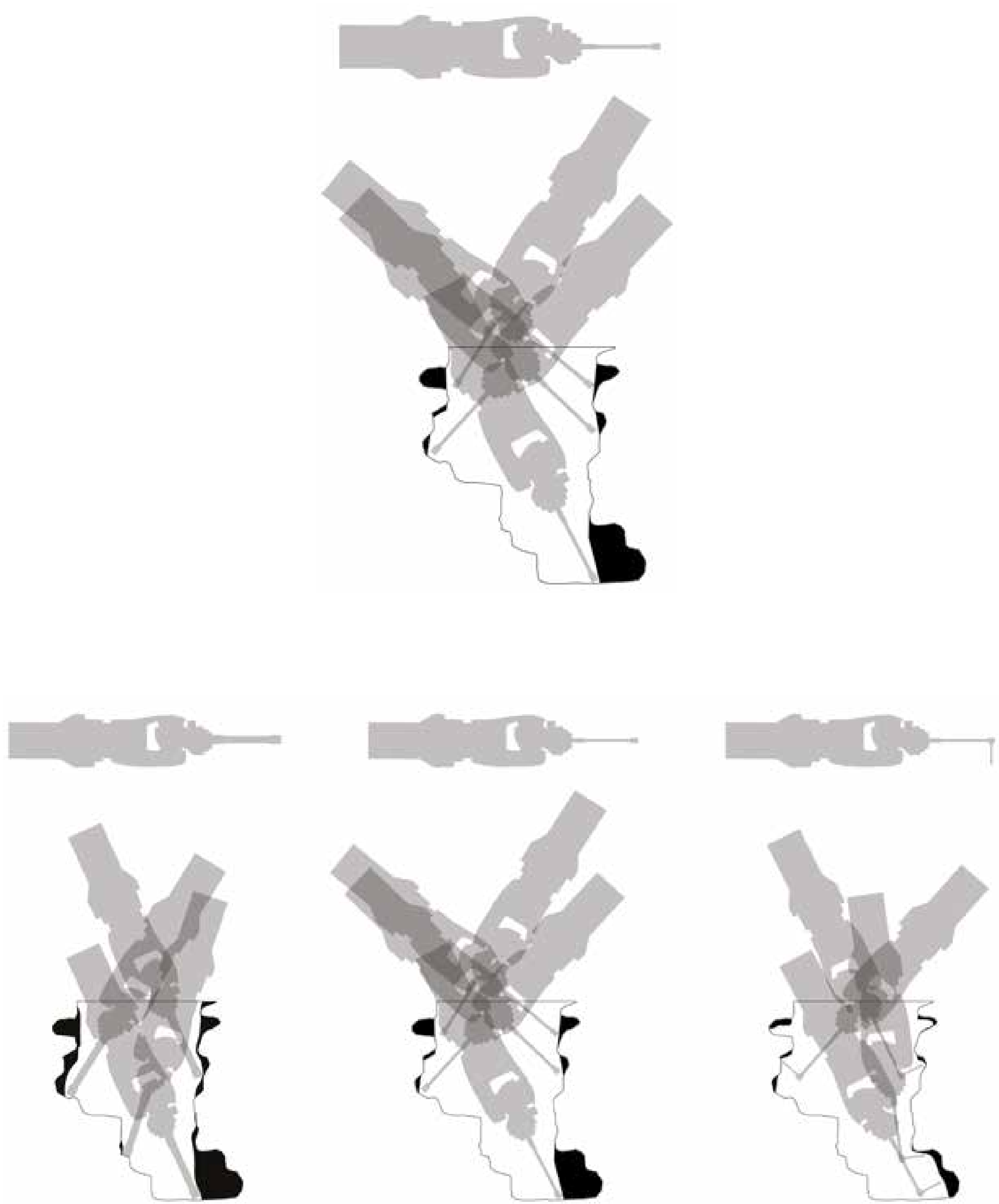


Fig. 7.37 Diagrammatic view of the robot-gap interaction during the experiment. In the center: extruded volume of the wall gap. The impossibility of reaching all the points of the volume adjacent to the pre-existing surface depends on the geometric limits of the end-effector which in turn are related to the limits of the extruder and to the motor that determines its functioning. The algorithm has been progressively modified and the outcome geometry revised based on the collision analysis provided by Kuka | Prc. Below: graphic representation of the extrusion simulations defined by the end-effector that was used and by two possible improvements of the final result.

digital design data to the behavior of the flying machines. The single-task performed by the drones consisted in taking hold of a polyurethane brick through an air system, performing the flight path and supporting the constructive element in the physical space as indicated by algorithm-based design. More recently, the use of drones in the construction of technological systems on the architectural scale has been the subject of research at the ICD (Institute for Computational Design) Stuttgart, with the Cyber Physical Macro Material project.[61] In this experimental context, drones were used to assemble the modular elements of an external shelter. The structure is programmed to dynamically adapt and reconfigure based on digital inputs that signal the user movement patterns to the central system. In a responsive way, the drones move the components which are defined by a geometry articulated by nodes with magnets.

The realization of the project outcome took place following a design interaction for the definition of the most effective end-effector for the extrusion of raw porcelain and in various steps forced by the need to let it dry to ensure adequate consistency and grip of the successive layers. The outcome of the additive manufacturing robotic test to fill a building gap is shown in the diagrammatic and photographic documentation (Fig. 7.36, Fig. 7.35, Fig. 7.38).

The construction phases to fill a gap through large-scale robotic additive layer manufacturing were simulated. The extrusion process needed to be divided into four sessions, ie the volume was created in four days. This four day process allowed the material to dry during the night and not collapse under the weight of the subsequent layers. Moreover, the script generated by the digital algorithm containing the robot's toolpath has been exported in two parts, due to the limit of the robot software to be able to read files that do not contain more than 703 lines of code, including within a disk space of 65 Kb. Circumstantial conditions such as: budget, timeframe for setting up the experiment, material availability of the people involved in this research and laboratory tools have meant that the first implementation test resulted in the final outcome. However, all the improvements and technical optimisations that can be made in a possible future development will be taken into consideration, to improve the print resolution and the effectiveness of the end-effector to reach all the target points (Fig. 7.37) defined within the project objective in the simulation phase digital.

61 Cyber Physical Macro Material at ICD Stuttgart: https://icd.uni-stuttgart.de/?p=23178.

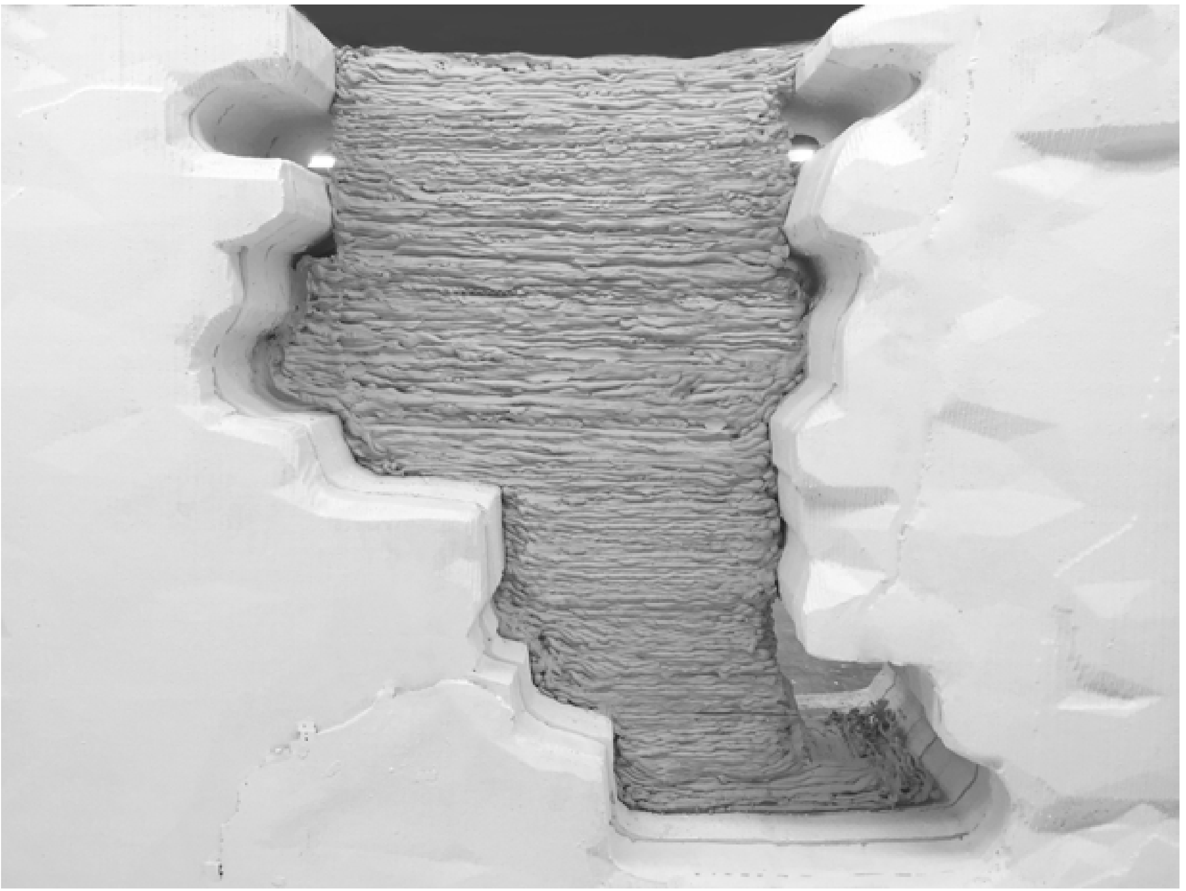


Fig. 7.38 The final outcome of the experimentation. Realization of robotic additive layer manufacturing to fill a wall gap on a full-scale foam mock-up.

7.6 References

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PART IV - TECHNICAL LAB EXPERIMENT

8 Validation of the experimental results

ABSTRACT

The following chapter consists in the evaluation of the lab experiment and the consequences in terms of skills, technology, and approach to Cultural Heritage.

The research experiment followed a pattern determined by a main objective and 3 secondary objectives. The structure of the experiment considered technical and theoretical aspects investigated in order to define limits, potential, and future developments. The main research objective organized applied research as a simulation of construction site operations. The objectives derived from the execution of the process concern the necessary skills, the technical issues addressed, and the outcome in terms of an architectural technological unity. A summary of the objectives introduced in the previous chapter follows.

Process validation resulted in a workflow and the experiment was considered an MVP. In this research context, the acronym MVP represented a minimum viable product. It was a minimum viable prototype or concept test, designed to test the hypotheses. The MVP / prototype of workflow could be replicated, deployed in different contexts, and transformed as appropriate.

Unlike those workflows that deal with the digitization of heritage, this research extended the digital planning to the production phases of the construction process. The experimental output is therefore not only a final dynamic model, but it operates as a built model informed by the technological outcomes obtained from digital fabrication. This prototypical workflow was divided into four main parts, which emerged from a metaproject phase. The early stage decision to produce an architectural object of intervention defined the critical approach to the project. The operative phases of the experiment were identified as: analysis, design, fabrication, and construction.

Moreover, it is foreseeable the possibility to carry out interim, low cost, realization of the workflow. That is, it will be possible to proceed gradually with the implementation of the technology before reaching increasingly high levels of sophistication. In this scenario, architecture is considered a driving force that is a synthesis between theory-practice-culture-social organization and work.

Keywords: *Research Validation, Workflows, MVP, Operators of the Fourth Industrial Revolution*

8.1 Restatement of the objectives

"The future is already here, it's just now evenly distributed [William Gibson, 2003]

The research experiment followed a pattern determined by a main objective and 3 secondary objectives. The structure of the experiment considered technical and theoretical aspects investigated in order to define limits, potential, and future developments. The main research objective organized applied research as a simulation of construction site operations. The objectives derived from the execution of the process concern (1) the necessary skills, (2) the technical issues addressed, and (3) the outcome in terms of an architectural technological unity. A summary of the objectives introduced in the previous chapter follows.

8.1.1 Primary objective

The primary objective of the experiment was to carry out an additive robotic manufacturing process on a pre-existing, complex geometry to simulate an in-situ restoration process. This workflow was the starting point and a proof of concept that was considered a prototype, which in market formulas would be identified an MVP, or minimum viable product / process (Ries, 2011). In the market, an MVP is a product with just enough features to satisfy early customers and provide feedback for future product development. MVPs are typical elements of start-ups, which make experimentation a tool to improve and get to more robust processes.

In order for this experiment to be possible, it was necessary to go through the experimental phases in order to identify the various languages and motivations of the different aspects of the work. A robotic additive manufacturing process, if observed at a large scale, in relation to a pre-existence is determined by the interaction of different skills. The starting point was (a) the language of robotic programming and (b) the customization of production through additive manufacturing (AM). The robot belongs to the programming / scripting language, while the AM refers to the decomposition of the geometries to be extruded into layers that become the final toolpath. An additional language at the base of the process is the understanding of (c) the geometry of forms three-dimensional space in which people and machines are located in the physical world. The technical language must be (d) at the service of the cultural instances, in this case referred to the conservation of cultural heritage. Finally, (e) the organization of the site and of the work groups is the main theme of the workflow and represents a topic of interest in particular for the future developments of the discipline. Evaluation at this stage of the TRL will be a starting point for determining the extent of possible future developments.

8.1.2 Secondary objective - skills evaluation

A key part of the experiment was the skills evaluation, that was the understanding of the factors that, together with the economic component and the investment risk, today constitute a barrier to entry in this field of research. Therefore, the organization of an applied workflow made it possible to verify the availability of information on the level of university education. In this regard, the experiment evaluated the cognitive abilities and gaps of researchers with cultural background in architecture and expertise in digital fabrication. People (students, research assistants, professors) have generic and non-specialist skills within the workflow. This non-specialized skill or naïveté of the principal researcher was considered an element of strength as it reflects the initial experimental condition for the deployment of robots used on-site.

At a time when robots become more operational in construction, there will be no examples of best practice to reference. It will instead be necessary for there to be professionals capable of identifying the complexities already known, or that will learn through operational experience, and be able to point in the right direction. Solving some problems in a laboratory with a low-engineered condition was effective to highlight issues worthy of further study in view of real applicability in architecture. Disclosure of the constraints in which the research was developed was also viewed as an occasion to make a contribution to the university on possible topics to be introduced in the curricula to prepare the next generation of students to face the challenges of the Fourth Industrial Revolution.

8.1.3 Secondary objective - technical evaluation

Understanding the technical language of the various phases of the experiment was necessary to understand what skills are needed and in which phases. Starting from the survey of a building to the production of a technological unit required the understanding of digital data processing skills. Digital representation of geometric or information models is a skill already present in the architect's background while scripting and digital fabrication are areas that are not yet the state of the art in many universities. Different digital languages were identified in carrying out the work. A first language was that of the parametric project that underlies the understanding of the calculation algorithms, the second consisted of the geometry of the project outcome in relation to the work area of the robot, the third was that of the kinematics for the execution of the RAM (robotic additive manufacturing) and the last language corresponded to the CAD-CAM translation for the realization through desktop printers (DIY end-effectors) of the actuators to be installed on the robot. The decoding of these different languages was essential to optimize the production phase, in order to coordinate the kinematics with the extrusion methods and times, also on the basis of the physical capabilities of the material. The research group pushed knowledge as far as possible (in predefined times and costs), in order to complete the laboratory activity, recognizing limits, languages, potential of each phase and consequently knowing how to identify the resolution of technical issues. An important technical aspect was the fact that part of the equipment was a used robot, repurposed from the automotive industry. This condition is likely in the first future trials of robots on-site. Before reaching an adequate TRL for the introduction of integrated instrumentation (robot-sensor-IOT) on the market, it is possible that investments in the construction sector for the installation of machinery are carried out on technologically simpler less capital-intensive robots, which may arrive from other sectors. Therefore, it was important from this experiment to develop a universal knowledge based on generic robots so that any outcomes could be more easily transferable.

8.1.4 Secondary objective - evaluation of the outcome for restoration

This last objective depended on the motivations expressed in the introduction, and consisted of moving the analyzed technologies and workflows towards restoration. Market indicators show that, especially in Italy, the aging of the existing real estate assets, the lack of investment in new buildings, and the growth of extraordinary maintenance costs open up to a wide potential market for existing interventions. In addition, interventions on existing culturally relevant buildings stimulate a more intense debate on the cultural aspect of the project. The execution of the design outcome takes as a reference the compositional language, the color, and the level of detail of the architectural technological unit produced. More important, however, will be the understanding of the relationship between new and historical construction technology. These changes will bring about a digital transformation of the craftsperson given the level of human-machine interaction in the process.

Finally, it will be essential to make a statement on the importance of the architect that represents the system and skills necessary for the realization of the project, operating as a master-builder and actuator of the Fourth Industrial Revolution. These objectives were met by the experiment. This experiment depended on the budget, time, tools, and the knowledge, experience, and skills available. To facilitate the reading of the evaluation, each objective was investigated on the basis of the expertise to which it was necessary to draw for the execution, the labor involved in the different phases, the team, and the material used. The rating scale is low-medium-high.

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-high	Low-medium-high	Low-medium-high	Low-medium-high

The metric for success of this rubric was not necessarily determined by the achievement of a high asset for each category. The objectives were considered achieved if these conditions were verified:

- understanding of technical and cultural languages on which the work of advancing the state of knowledge was based;
- understanding of the technical complexities that took place in each phase of the workflow;
- understanding of the skills needed to complete the workflow from design to execution of outcomes;
- confirmation of the technical and theoretical premises that moved robo-technologies towards restoration and, more specifically, towards the restoration site;
- the definition of the current TRL in order to determine the methods and opportunities for future development.

8.2 Validation of the primary objective: definition of a workflow

Applied research simulated a future scenario defined on the basis of trends analyzed in the construction sector, particularly in Italy. The simulation took place in a low-cost work context. To maximize the experimental results, decisions were made to operate under specific constraints and reduce the resulting complexities. On the one hand, mapping the constraints and disclosing the complexities serves to introduce a workflow prototype into the research sector, making the phases explicit, which can be developed by other research groups, starting from these results. On the other hand, this construction process simulation can help to outline a professional figure capable of managing the first robotic construction processes with low capitalization costs. The work has been mapped as "low" in all the categories, characterizing it as a low-budget, entry level approach:

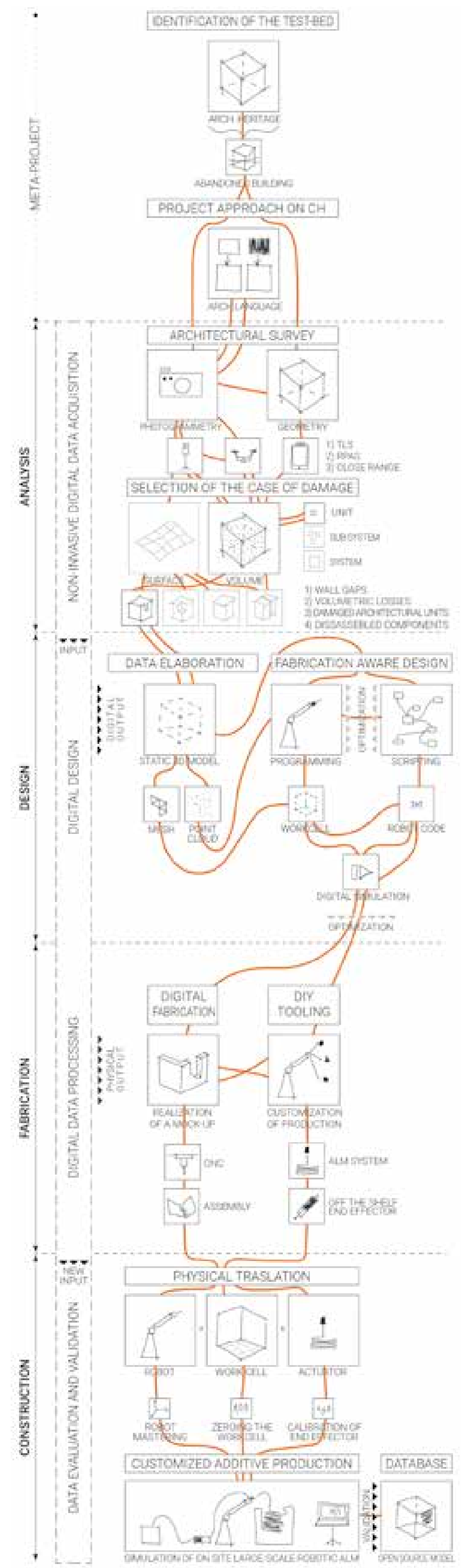
1. no previous exposure in robotics and large scale AM;
2. student labor deriving from the university background of studies in architecture, that is grad and undergrad research assistants at the LTU institution with a consolidated experience of digital fabrication at desk level;
3. equipment typical of a fablab, consisting of 3D desk printers and with the addition of an industrial robotic arm;
4. low engineered material, necessary to synchronize the kinematics with the theoretical building production.

This means that the principal investigator / author, personally worked for the first time in this type of process. The inexperience was viewed as an opportunity, knowing that when the first robots will be used in an existing recovery site, they will find themselves for the first time without a deep operator experience or knowledge base. Probably before the guidelines are established at national and supranational level, the process itself is going to be hacked and adapted to the different construction needs with a DIY strategy given the low capitalization costs in the construction sector.

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-high	**Low**-medium-high	**Low**-medium-high	**Low**-medium-high

Process validation resulted in a workflow and the experiment was considered an MVP. According to the definition of Eric Ries, a minimum viable product "that is the fastest way to get through the build-measure-learn feedback loop". In this research context, the acronym MVP represented a minimum viable product, meaning that "an experiment is more than just a theoretical inquiry; it is also a first product" (Ries, 2011). It was a minimum viable prototype or concept test, designed not just to answer product design or technical questions. Its fundamental goal was to test the hypotheses (Ries,2011). The tests that are carried out as an MVP are used to indicate if a product should be built and if there is enough interest to continue with feasibility studies to achieve more structured goals in the future.

Digital Workflow - LABORATORY EXPERIMENT



The MVP / prototype of workflow could be replicated, deployed in different contexts, and transformed as appropriate. With any experiment, limitations and constraints exist that are worth acknowledging so that subsequent research may begin with this understanding. The resolution of the wall gap experiment is in fact a starting point for a much broader application.

Among the international research projects that have disseminated operational workflows, Inception and the Time Machine Project were included in the case study portion of the research. Both projects structured their research phases with a workflow scheme organized by work sessions. Unlike those workflows that deal with the digitization of heritage, this research extended the digital planning to the production phases of the construction process. The experimental output is therefore not only a final dynamic model, but it operates as a built model informed by the technological outcomes obtained from digital fabrication. This prototypical workflow was divided into four main parts, which emerged from a metaproject phase. The early stage decision to produce an architectural object of intervention defined the critical approach to the project.

The operative phases of the experiment were identified as:

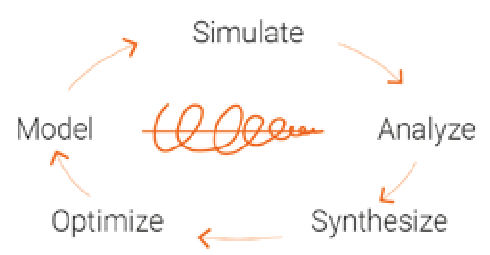
1. **analysis**
2. **design**
3. **fabrication**
4. **construction**

The workflow analysis phase focused on the geometric and photogrammetric acquisition procedures of the architectural property. This phase had several potentials:

- the digital model of the asset to be restored allowed for development and management of an entirely digital process. This process made it possible to proceed with several construction phases simultaneously, depending on the project requirements. Decision whether it was more effective to proceed with work on-site or with the production of custom elements off-site;
- the geometric data shared in order to collect a large database of information for the digitization of the heritage and speed up the operations of conservation and recovery;
- the same data integrated with the built-in models that help to track the changes that occurred in recent times on historical assets. In this circumstance it was possible to include information relating to the robotic programming that was necessary to achieve a specific constructive result.

The design phase was configured with the processing of survey data and the breakdown of the geometries into basic elements (polylines, contours) for the programming of the kinematics through which the robots performed the operations. This phase also included the design of the end-effectors configured as actuators of the customized architectural production. The main potential of this phase was configured as:

- possibility of simulating through interactive visualization the desired actions to take place in the physical world, in order to identify inefficient parts of the system or potential collisions;
- possibility of using the algorithmic tool to optimize the process at critical points.



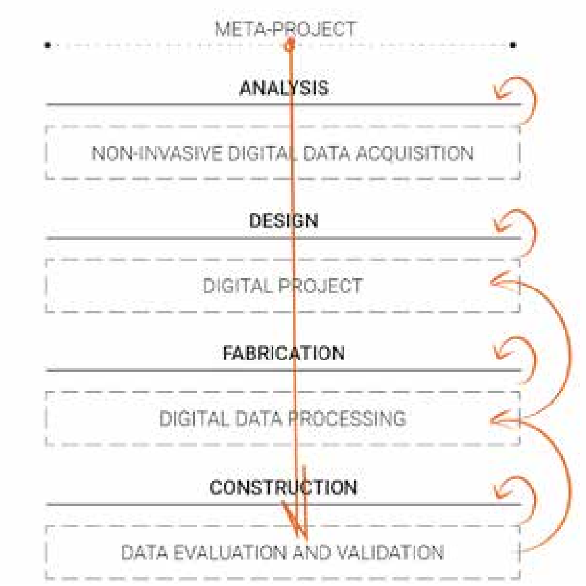


Fig. 8.1 Diagram that summarizes the use of technology: iterative design process informed by simulation and analysis of critical project parameters. Source: LMN Architects. Available at: Deutsch, R., 2015. *Data-driven design and construction: 25 strategies for capturing, analyzing and applying building data*. John Wiley & Sons, p.158.
Fig. 8.2 Fluidity of the workflow carried out during the lab experiment. The arrows indicate the possibility of iterate the process.

The fabrication phase involved, in parallel, the construction of the building prototype resulting from the geometrical survey previously carried out and the DIY realization of robotic end-effectors. This phase was fundamental to:

- formulate operational hypotheses regarding a simulation of on-site restoration intervention;
- perform tests in the physical world to validate the simulations carried out. This experiment worked within irregular geometry. This spatial constriction impacted the sizing of the end-effector, the modification of which induces modifications in the geometry of the toolpaths and in the execution speed.

The construction phase took place through the material transfer of a digitally constructed architectural unit. This step served to further validate the design hypotheses and to raise discussion points based on the analysis of the results. Validation was important to:

- acknowledge the cognitive level achieved within the process, after approaching RAM (robotic additive manufacturing) with an architecture background. Consequently define which competences were necessary to achieve the project objectives and which were educational deficiencies that can be integrated in the future in the university curricula;
- defined with which improvements it was possible to inform the process in order to obtain results that were each time more significant for the progress of the state of the art and technology readiness level.

The workflow combined the design culture with the technological culture. Through a single workflow that combined design and production, the designers had control over the formal generation process by shortening the distance between the digital and physical world. The developed workflow allows for the definition of a hybrid operational sequence that can be fluid by moving data back and forth from phase to phase (Fig. 8.2). The workflow was carried out with phases designated in a dynamic way, allowing interactions (Fig. 8.1) and optimization within each phase. This dynamic process resulted from the potential of CAD-CAM in which immediate communication occurs between matter and digital model. Retracing actions between phases was possible thanks to the customization of the project using production technologies and the tools programmed to perform them.

Inputs were not input data only at the start, but once the work moves to the next phase the input data can also inform possible iterations and optimization of subsequent phases. An example is the transition between design and fabrication. At the end of design and the start of robotic programming, virtual simulations are performed for which any errors in the kinematics are corrected. Following digital validation the work moved into the physical world to check if there was compatibility between axis movements and use of end-effector / actuators. The execution of the lines of code in the physical world can identify marginal aspects to be corrected, such as the repositioning of the "home position" (first coordinate of robotic code) or resetting values of movement speed. The optimization of these aspects informs the incoming data of the process iteration, defining a better output.

This iterative rationale was also applicable for some project variables that, in the absence of computer visions or sensors for real-time update, cannot be completely controlled by programming alone. For example, in the case of additive manufacturing it is possible to incur inaccuracies in the definition of the mixture of material to be extruded. The layers may get compacted under the weight after a certain number of layer overlaps. If this happens it is necessary to increase the contours or extrusion layers and therefore consequently reiterate the process with the new information derived from the physical feedback.

8.3 Validation of the skills

When this laboratory experiment began the author worked as an outsider in the field, as a non-expert who had to resolve various barriers to entry. This outsider-ness might map directly to conditions that other projects might face at early stages such as a lack of funding or a lack of knowledge. The cognitive tools that guided the process development started from a background of studies in architecture. Other people involved in the experiment shared the education background, which formed competencies in digital representation, parametric design, and workflow management in the decision-making phases. Individual study was carried out through interaction with multidisciplinary professionals and the use of open source resources. This individual study was necessary because small-scale digital fabrication is not taught extensively in all university curricula and results in uneven distribution of this skillset. The transition to robotic digital fabrication was more challenging as the main stakeholders are part of an exclusive community. The community consists predominantly of different online forums where researchers share their research experiences and receive feedback for solving specific problems. The advancement of the knowledge applied to the architecture sector therefore develops in a fragmented and non-unitary way with the skills development for the operation of these technologies. The positive aspect was that for robotic programming there are already work interfaces familiar to architects, which rely on algorithmic design plug-ins and 3D modeling software. Where architects lack some knowledge they are able to make up for it in other areas like the modelling and simulation side.

The lack of technological literacy (Aoun, 2017) related to robotics programming made it possible to identify all the complexities of disciplinary language not only of the technical aspects but also of the organizational aspects of the work group. The intent of this project was to simulate a construction process. However the experiment was not able to refer to any real, previous example because none exist. The TRL in the sector did not offer any cases already realized with on-site innovation, understood as a place where a "temporary coalition of people and organizations" occur (Groak, 2002). This experiment (and temporary collaboration) between researchers has led to the hypothesis for each phase of a working culture that has tried to respond to the requirements of the Fourth Industrial Revolution.

Based on the workflow generated by the experiment, it was possible to map the competences and to visualize the process that witnessed greater overlaps, or where greater integrated knowledge and interdisciplinarity is required. The experiment took the development of the different steps as far as it could in order to identify experts who might play a role if the decision is made to scale-up the process to the complex reality of the construction site. Such experts must also know how to work together, under the direction of an architect / operator of the Fourth Industrial Revolution.

The workflow systematization allowed for the visualization of what can be defined as a "vertical integration between digital design and digital manufacturing, and the technical continuity between digital tools for visualization, notation, and fabrication" (Carpo, 2011). This summary allowed identification of the different disciplinary skills needed to set the design strategy based on the use of data within a digital workflow. The result of the multidisciplinary experiment generated a non-generalist but specialized collective intelligence through which it was possible to model, elaborate, and interpret the data necessary to make decisions and therefore generate design solutions (Fig. 8.3, Fig. 8.4).

After analyzing the different steps of the experiment, desired procedural continuity would come through the support of:

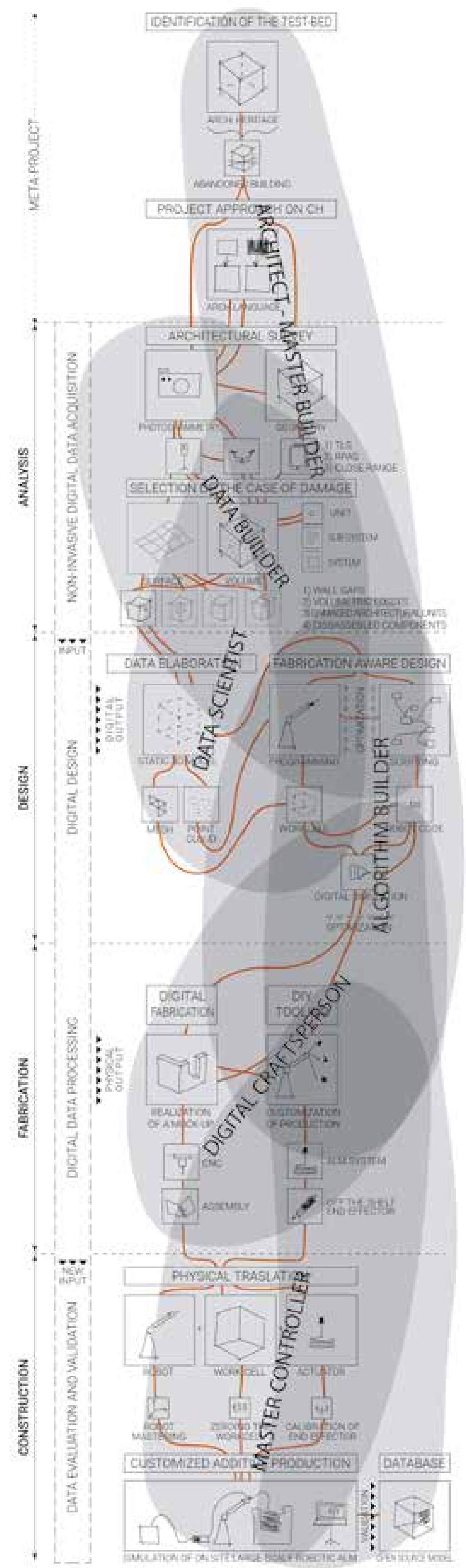
- data scientist, data analyst, or a figure able to solve data-driven problems and discern the most advantageous data to be exploited within the workflow;
- data-builder, that is a professional capable of processing input data and generating output data in order to effectively combine digital and physical worlds;
- algorithm-builder or scripter capable of defining digital rules of variability that govern both the design phases and the production phases:
- digital craftsperson or a person in charge of managing the CAD / CAM transition and the materiality of the output of the robot;
- master-controller able to manage the tools that allow the team to realize the customized construction phase.

These professional skills overlap at various phases and these points of convergence create the most consistent data streams because of the following:

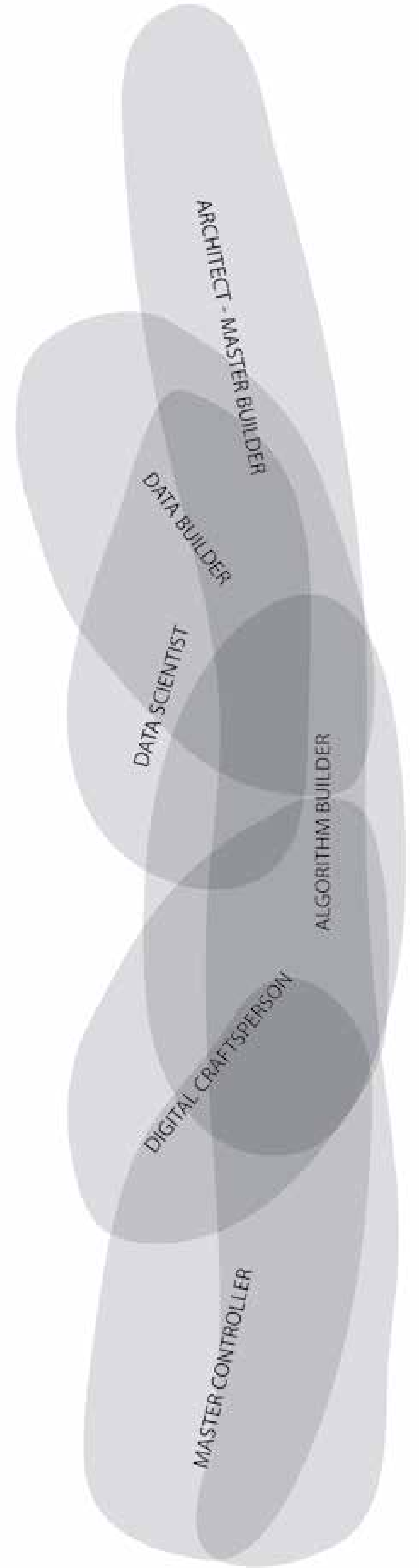
- the process through which the three-dimensional digital model is placed in the fabrication-aware design process and then broken down into simple elements which set the robotic schedule;
- the step that involves the design of the tools needed to customize the process and achieve the design objectives by validating the digital simulations.

It is clear that in the design, fabrication-aware, and CAD-CAM transition phases, a development of skills is required which are not yet fully part of the standard curricular offerings of university education. This acknowledgment gives way to start a reflection on the fact that in order to face the transformation that will start in the near future in the field of architectural design, it will be necessary to educate professionals able to combine multiple competences. By putting data scientists, data and algorithm-builders, digital craftspeople, and master-controllers as systematized collaborators, the

Digital Workflow - LABORATORY EXPERIMENT



Skills - LABORATORY EXPERIMENT



architect will become:

- a customizer (Deutsch, 2015) able to manage the complexity of digital variability and exploit the flexibility of robots to customize processes based on project objectives;
- a data-informed architect (Deutsch, 2015) capable of exercising an integrated design, not fragmented as it currently appears in architecture, in which the aspects relating to the ideation and construction phases are considered as part of a single process;
- a digital heritage hacker, able to integrate analysis data to digital fabrication data for the production of customized architectural units;
- an operator of the Fourth Industrial Revolution, able to manage the digital complexity derived by tools, software, and methods 4.0.

In order for this design scenario to be reflected in the applicability of future processes, the design culture must become more collaborative as more skills overlap will need to occur.

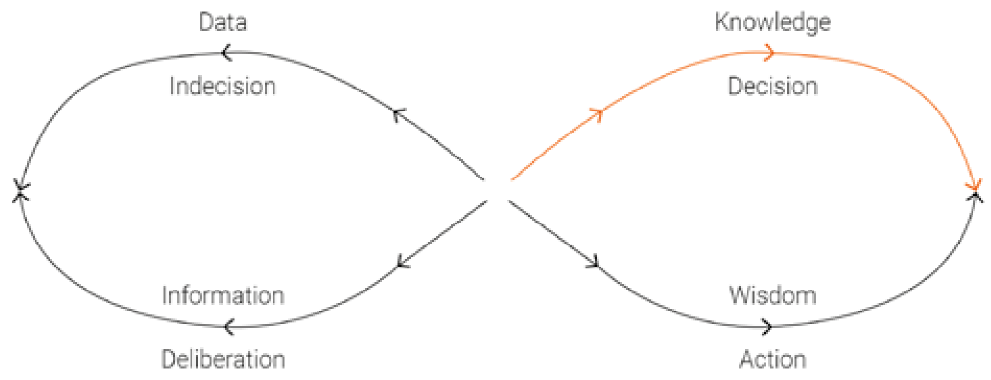
8.3.1 Skills limitations

The experiment highlighted the competences that can easily be integrated in the architecture curriculum. Cultural knowledge about the Second Digital Turn must be integrated and not fragmented. This skill result can be achieved by making the tools of the Fourth Industrial Revolution ubiquitous in higher-education, so as to form generations of designers better oriented towards fabrication-aware design. These changes will then bring about broader procedural advantages for the architectural project. At this transitional moment, CAD-CAM still represents a limit at universities. Universities should be environments to develop skills to manage small-scale and large-scale tools for customized production. The application of robotic and automated technologies will have to become common in order to mature the necessary skills for future designers. This will allow the diffusion of the proposed operating methodology and tools for application within the reference market . The skills gaps is limiting students and relegating them to second level specialized training courses instead of being introduced to the topics starting from the first cycle of university education.

The inability to locate best practices will also continue to limit experimental outcomes and education. There are at least three software plug-ins for simulating kinematic and at least three robot suppliers in the architectural robotics community and this fragmentation makes it difficult to identify tactical operational support. While projects and outcomes are disseminated, the introductory steps to operating or setting up a robotic system are either outside the reach of novices or viewed as too low level by experts to share. Companies charge for their services for setup and this can represent a financial hurdle for aspiring architecture programs hoping to enter into this area of research or education.

8.3.2 Skills potentials

The recognition of the different working languages allows for the identification of a future professional figure that will be able to mediate the skills, languages, and motivations of specialists. This person must interpret and synthesize diversified skills ranging from architecture, engineering, materials



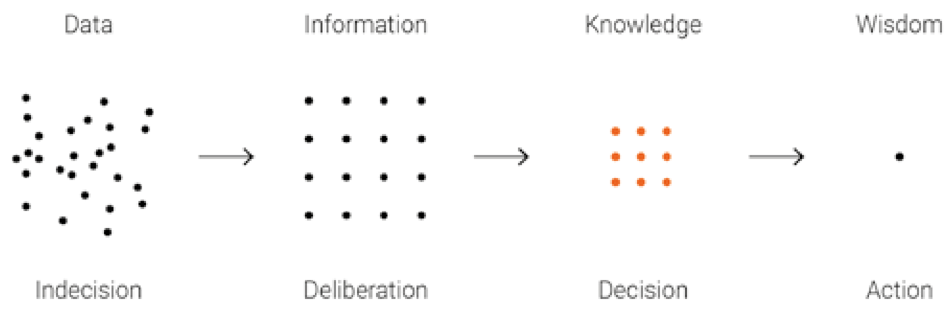


Fig. 8.3 According to Randy Deutsch, a design process can be summarized as a sequence called DIKW (data, information, knowledge, and wisdom). It is "a continuous loop towards increasing certainty". Source: Deutsch, R., 2015. *Data-driven design and construction: 25 strategies for capturing, analyzing and applying building data.* John Wiley & Sons, p.6.
Fig. 8.4 A different way to explain the DIKW progression: "leveraging data to manage complexity". Ivi, p.5.

science, computational design, and programming / scripting. This master-controller, or operator of the Fourth Industrial Revolution will be the benchmark of the construction site as was the medieval master-builder and will bring together the collective intelligence based on information technology. This operator will be able to identify the issues and direct the issues to the competent expert.

The understanding of computational languages also allows for a controlled dialogue with the tools and at the same time to predict what the machines are capable of doing and generating as output. This knowledge allows them to know how to manage the entire process accordingly. The interaction space between designers and digital tools will allow for the investigation of new manufacturing methods and stimulate creativity through a process of collaboration between different expertises. Digital manufacturing specialists possess the knowledge necessary to break down design problems into simple parts, through a new material sensitivity that is the result of customized manufacturing processes. The systematization and simplification of problems aids in the subsequent optimization. In this context, parametric software is fundamental for the control of the entire design chain but not sufficient if not supported by a parametric design idea. If supported, this tool can synthesize and manage the process using computational models.

The contemporary redefinition of the architect could be marketable by encouraging industries to collaborate between education and practice. This type of collaboration can initiate a process of innovation within the construction processes and place the most suitable tools in the correct hands thanks to a real-time feedback from the actors in the design chain. To amplify this concept, it is believed that industrial-type applied research ensures that investments are shared with the production companies that in turn benefit from them with regard to process and product innovation. Robots and 3D printers can develop a material culture of learning by doing in an academic environment. These tools can reorient the design and production of a specific product, paying more attention to the process than to the final realization. In post-digital perspective, this concept evolves the learning by digital fabrication (Oxman, 2008). This type of cognitive process will be able to train architects prepared to manage digital complexity characterized by 4.0 tools and processes.

8.3.3 Future developments of the skills

In the future, the dissemination of skills will be increasingly accelerated by the reduction of the costs of the tools (Fig. 8.5). The dissemination of information and open source software that rely on open communities of developers will also reduce the investment necessary for the software and for the development of the emerging design tools. Future development trends indicate that the ToA (technology of architecture) discipline will witness an exponential democratization of software and hardware, definitively paving the way for innovative educational paths. Higher education plays a fundamental role in developing a learning model for the future (Ford, 2015) corresponding to the democratization of automation tools. This underlines how the designers find themselves in a position to lead these processes in the future.

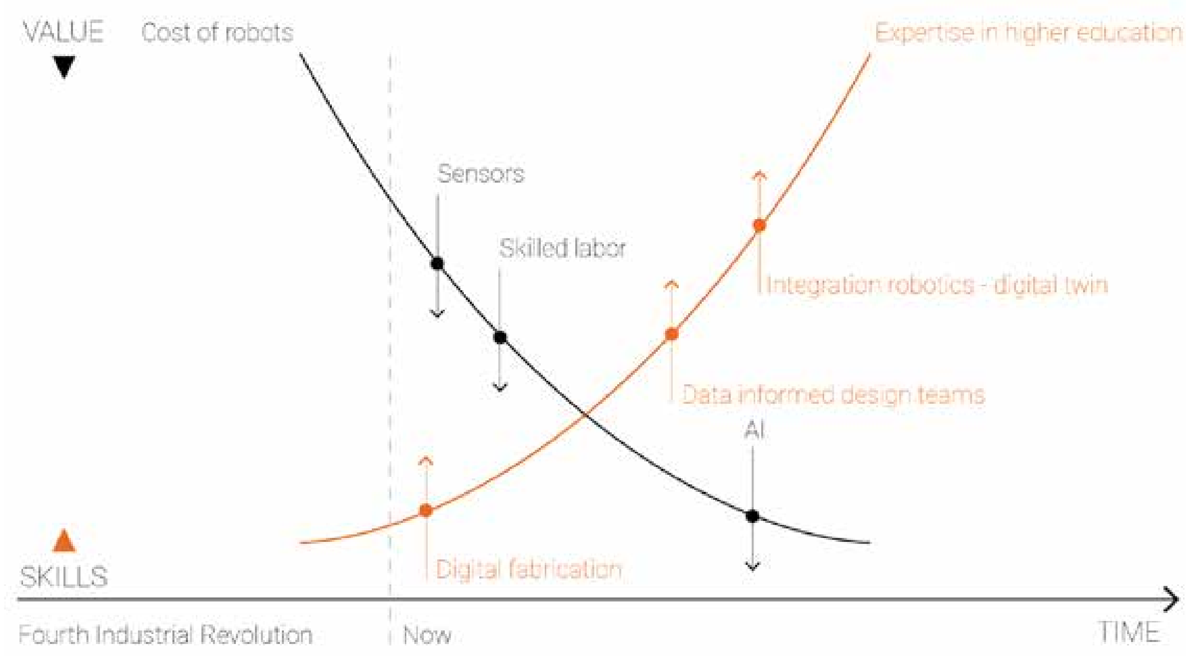


Fig. 8.5 The role of Higher Education in relation to the democratization of robots, in the context of the Fourth Industrial Revolution; simultaneous diffusion of knowledge on the use of new technologies in innovative sectors and lowering of the industrial robots' cost. Research on AI and sensor technology contributes to the lowering of their value in the market. At the same time, the lack and consequent increased cost of skilled labor encourage investments in automation. Moreover, the academic sector is opening up to teaching digital fabrication at different scales of application. In this way, the next generation of professionals will be able to work in multidisciplinary teams informed by data.

Taking up the classification proposed above, the development of the future methodology can be centered on the maturation of the skills. Skilled people will work in compliance of future protocols for IoT and digital manufacturing processes. Theoretical knowledge is guided by computational thinking, through which all the competences involved in the design process are structured in the form of data.

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-**high**	Low-**medium**-high	Low-**medium**-high	**Low**-medium-high

It is increasingly evident that future operators in the AEC industry[1] will need more technological awareness with respect to the constant evolution of design and construction technologies. In this scenario, theoretical and application concepts such as those of variable, function, relation, input / output, recursive, and interactive process need the presence of a mental process that is at the basis of the formulation of problems. Solutions to these problems can be represented in a form that can be processed effectively by a computational tool capable of receiving these inputs.

8.4 Validation of the technical assets

This experiment was considered concluded in terms of proof of concept. The elements that emerged from the laboratory experience laid the foundations for a more informed discussion about the approach for using additive robotic fabrication on pre-existing geometries extrapolated from relevant historical buildings. This feasibility test is a starting point for greater applications, starting from academic research to that which can be carried out on a larger scale with industrial partners. The evaluation of the technical aspects is a category in its own right as it is rich in variables, all linked to the communicability of the tools in the digital environment and then, by translation, in the real environment.

Workcell

In-situ robotic work was simulated. To simulate existing site conditions, a robotic workcell was created with geometric obstacles that were avoided. The digital model of the wall prototype was used to both calculate the robotic path and minimize the number of collisions, relative to each target point defined by the density of the toolpath interpolation. The geometry of the wall gap (intended as a workcell unit) determined the shape of the end-effector, that was initially modeled digitally. The wall was positioned in the workcell and set to zero by identifying coordinates in the reference space and by measuring the distance between the robot's home position and numerous points on the prototype surface. To have added certainty of the correct positioning of the object in space, the geometry of the work platform (stage) was divided into a grid so that each intersection corresponds to a triplet of xyz coordinates which in turn have been transferred into the software for the digital simulation.

1 AEC industry: http://www.imscadglobal.com/industries-AEC.php.

End-effector

The end-effector was the result of a series of factors, including geometry, location, and the power of the stepper motor. It was possible to use a nozzle (d=4 mm) whose TCP (tool center point) constituted a linear translation along the center of gravity of the A6 axis. Deviating the placement of the TCP would have been useful to increase an A7 axis of flexibility for the robot. This change would involve revisiting different parts of the hardware and may be taken into consideration for future research developments. The design of the end-effector could be improved based on the geometry of the existing undercuts of the wall gap. Being able to fill all those areas of the wall gap with material would require the use of a nozzle thin enough to fit within the thickness of the extrusion layer and long enough so that the robot head does not collide with the wall section or with the layers of previously deposited material. In this experiment, this part of technical criticality has been partially solved. Laboratory optimizations of the robot end-effector large-scale extrusion ratio are necessary before carrying out applicability checks on-site.

Material

The use of a liquid-viscous material such as raw porcelain gave the advantage of bringing the dimensional tolerances closer to a half-centimeter scale. Slowing down the robot's kinematics was enough to expand the thickness of the layers until they were completely adjacent to the surrounding surface. Therefore, adjustments could be made real-time, physically, by operating on the teach pendant during the execution of the robot code. The extruded material adhered to the irregular horizontal and vertical surfaces of the gap's edges. Although the low-engineered material was of simple formulation (water and industrial porcelain premixed with grog), it adapted well and gripped the formwork. The observation of these aspects of material behavior opened up hypotheses on the performance characteristics that a possible high-engineered material[2] could have for similar processes in more permanent applications. It is possible to hypothesize an extrusion of an architectural unit or directly depositing a quick-hardening paste with a robot to restore a non-bearing missing part. The restitution of structural parts can also be governed if the carrying capacity of the existing structure and materials is known, if the interface surface is understood, and if the level of collaboration between the load-bearing system and the new insert is known. The research experiment also tried to bring to light more knowledge related to the control of the kinematics of A1-A6 in relation to the extrusion. The use of high-performance materials must take into account the minimum and maximum speeds with which robots are able to operate. Consequently, materials must also define the properties that, once extruded, are already able to reach positions, thanks to accelerating gripping additives for example or modifying flow rates capable of withstanding subsequent extrusions. The stability of the extruded material at a constant speed provides the possibility of accurately predicting the construction times within the workflow.

2 This would involve the translation of the base material from low to high engineered and the experimentation of innovative mixtures from which the study of alternative aggregative systems of technological units can derive.

8.4.1 Technical limitations

The experiment was divided into multiple operational sequences, each of which was characterized by specific elements of complexity. In the final execution, not all the technical aspects have been solved. To push subsequent optimization of the workflow, further research is needed. From a technical point of view, on the one hand, the outcome of the work gave a nod of positive feedback on the scalability of the processes, on the other it highlighted the limit in the management of tolerances. This limit derives from the inaccuracies found in the production process in the absence of sensor instrumentation with which to implement a feedback loop strategy for monitoring the additive phase and the modifications of the extruded material. The analysis of the results highlighted the limits of the work carried out and the potential for future development.

Applied research was carried out according to a sequence of technical objectives to be achieved. With the same logic, aspects worthy of further study are listed below, to cover some technical limitations that occurred:

- the dimensional constraints of the work cell, or work space, limited to the radius of operation of the robotic arm;
- the management of the production process in relation to the tolerances and dimensional variations that occur in the executive phase, generating errors that increase as the operations follow, requiring to update the robotic programming script on the basis of the new geometric conditions reached;
- the lack of predictive information on the behavior of low-engineered material in order to make the most of its physical capabilities and to structure the input data in the experimental early stage;
- the lack, in the computational process, of simulation phases of complex phenomena such as structural analysis;
- the construction of the extruder to be installed on the head of the robot on the basis of open source information given the absence on the market of the tools necessary for the completion of the experiment;
- the calibration of the robotic end-effector and the precise correspondence of its geometry in physical space and in digital space, as a non-standard element;
- the need to design a method to match the building prototype in physical space and digital simulation, by recording spatial coordinates;
- the impossibility of filling through the automation process, all the undercut areas of the gap volume. This was due to the lack of suitable professional skills within the workflow to speed up the performance of some phases and thus allow for improved iterations. This is a crucial point since the undercut elements are those that constitute the greatest danger during construction phases.

8.4.2 Technical potentials

The proposed methodology has great potential to effectively address construction problems that are still current, optimizing the real-time responsiveness of the tools used based on the work cell in which they operate. They have therefore been identified as potential elements:

- the use of innovative manufacturing tools such as RAM - robotic additive manufacturing allows the customization of constructive components and makes it possible to operate ideally in the times and costs of mass production;
- the possibility of generating design outcomes through a low-cost operational methodology that allows for digital computing, material experimentation, and innovative production processes that can encourage the spread of technological thought. In this way the various researchers involved in the experiment were able to direct and adapt their knowledge to carry out a new process;
- the possibility of iterating phases of the project in a way that is not necessarily consequential, so as to guarantee the effective producibility of the components;
- the possibility of implementing an additive manufacturing procedure in correspondence of horizontal and vertical irregular surfaces using a low-engineered material;
- the possibility of implementing the software used for the programming through plug-ins able to expand the kinematics possibilities;
- the possibility of defining the work area, deciding on the placement in the tools space by relating digital and real workcell;
- the possibility to exploit the algorithmic tool for inclusion in the workflow of descriptive geometric and kinematic parameters of the project within the process and simulate virtually different design hypotheses;
- the possibility of creating an architectural technological unit on a 1:1 scale through a highly customized process, in an existing geometric context;
- the possibility of producing a tool, end-effector, customized actuator to be used in the production phase of the experiment;
- the optimization of material resources, with a view to sustainable design with control of the use of resources, for digital fabrication through the decomposition of complex geometries into simple robotic kinematic paths obtained through the use of generative algorithms;
- the possibility of simulating the production process in a digital environment and displaying the operating sequences in order to correct collisions or singularity of the robot axes;
- the possibility of using the same end-effector in different complex geometric contexts, for customized production or consolidation of existing architectural units;
- the use of material only where needed, through RAM, without wasting resources and improving implementation times. Through additive robotic manufacturing it was appropriate to minimize the use of internal material in favor of the elaboration of a non-structural hollow volume. This was determined initially by the fact that the manufacture of a full volume would have required a large quantity of material. This amount of material would have had to be inserted in a container much larger than the one used, requiring numerous refills, slowing down the production process;
- the possibility of using design interfaces already widespread in architectural practice, such as algorithmic design software and translating this computational language[3] into robotic programming.

3 "Algorithms are usually expressed in text. This text is written in a language. All languages have two components: 19 a lexicon of allowable words (or other tokens) based on an agreed alphabet or sign system; and 29 a way of combining those elements legally, the syntax. See: Coates, P., 2010. *Programming. architecture.* Routledge, p.2.

8.4.3 Future developments of the technical assets

Looking at the experiment in a broad way, or by including all the technologies involved, the work can be categorized within the NASA classification of the TRL. It is the set of conditions for the state of technological appropriation of a given innovative process. The state of the art of knowledge from which this work began was defined as TRL3. TRL3 requires having "documented analytical / experimental results validating predictions of key parameters". The research pushed this condition towards the next technology readiness level, TRL4, which consists of "documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment". The experiment is classified in the group "research to test feasibility" (Fig. 8.7) of progress in this field and to encourage common interest in other research centers.

It is possible to imagine a scenario of the proposed methodology in which importance is given to the development of technical aspects (Fig. 8.6) through specialized skills. This experiment aimed at addressing the specific complexity of the construction site, innovating the predictability, and responding in real-time for the creation of components.

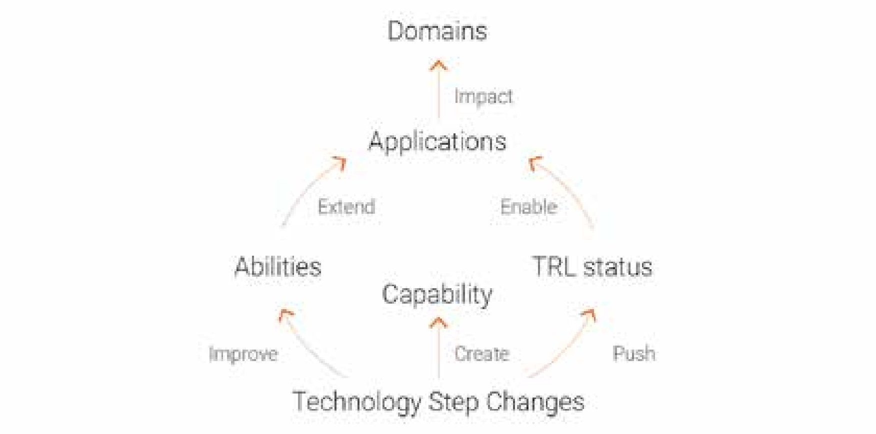
Expertise	*Labor*	*Equipment*	*Material*
Low-**medium**-high	**Low**-medium-high	Low-medium-**high**	Low-**medium**-high

The technical development potential could be greatly expanded given possible integration of tools with AI technologies, machine learning, and feedback loops through the activation of sensors. These elements are expected to be fully integrated into robots in the near future, which today are still produced in a generic way to carry out codes that drive kinematic movement. The integration of soft tools is a condition that can determine the definitive adaptation of industrial machines for architectural production especially under conditions with sensitive context. In this way it is possible to exploit the potential of the IoT and dynamically manage the available data flows.

The use of integrated technologies can:

- give the robot cognitive skills that allow it to relate in real-time physical space with digital space and vice versa. This is possible by integrating the hardware with an AI system that allows for the design of adaptive models capable of making modifications to the digital model in relation to the manufacturing process. In this way, the objective of reducing the problems relating to tolerances and consequently making the production process more efficient can be pursued;
- expand the workspace so that it does not constitute an operating limit. This objective can be pursued by equipping the robot with a mobile platform or by adding external linear or rotational movement axes;
- complete the design of the end-effector with a system of sensors through which to manage the manufacturing parameters in relation to changes in real conditions;[4]

4 Innovative work is being developed in both academia and industry for the additive deposition of material with



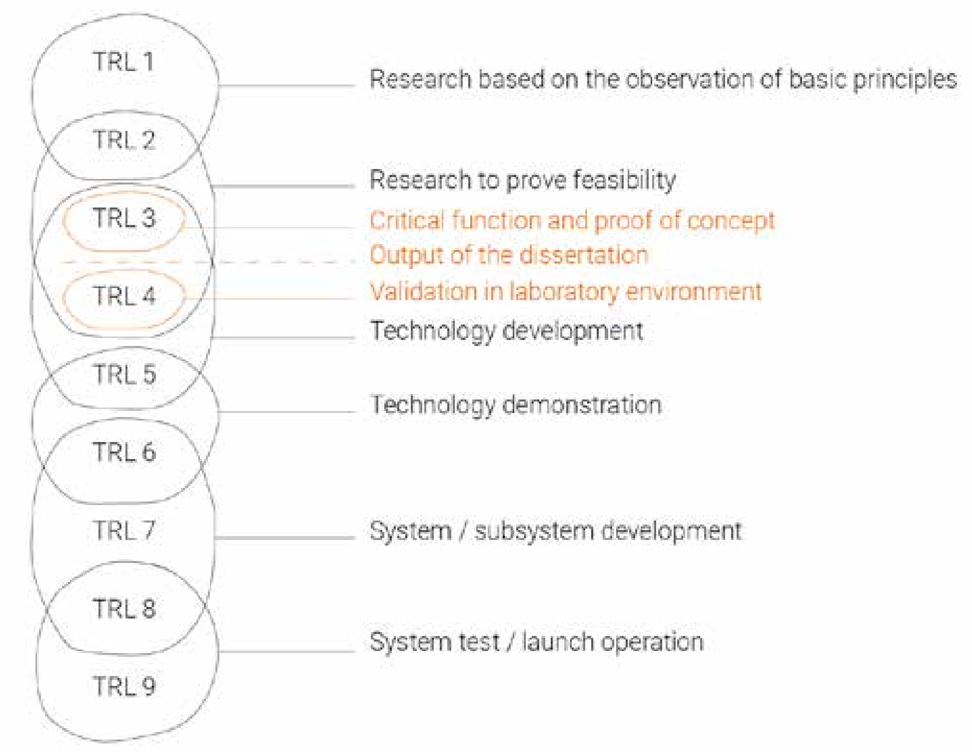


Fig. 8.6 Relevance of the TRL to enable technology applications in different sectors. Source: Robotics, S.P.A.R.C., 2016. *Robotics 2020 multi-annual roadmap for robotics in Europe*, p.9.
Fig. 8.7 TRL definitions, according to the NASA classification ad adopted by the Europan Commission. Available at: https://enspire.science/trl-scale-horizon-2020-erc-explained/.

- allow for the study of a high-engineered material that can constitute an interface compatible with historical architecture. Its tuning must be combined with optimization processes that allow the weight of the structure to be reduced, optimizing the distribution of the material in relation to the distribution of the loads and controlling stiffness / weight in relation to the performance characteristics to be achieved.[5]

Future implementations of the experiment may involve the design and manufacturing phases. To support this development, it will be necessary to include digital programming skills and materials science in the various phases of the workflow.

8.5 Validation of the outcome for Cultural Heritage

The experimental output has the character of a full-scale study model as it allowed for the investigation and verification using actual material but in a simplified set of conditions. The experiment confirmed the fact that this methodological approach can support an expert in conservation, who can dictate the design approach and define all the project variables to be respected in order to achieve the optimal conservation result, based on the dictates of the discipline. Professionals operating in a delicate sector such as heritage conservation will have the advantage of exploiting the digital data collected through digital surveys and using the digital survey to generate predictive models that reduce the uncertainty of operations. The architect will be able to exploit the construction and materials given the opportunity to develop new aesthetic sensibilities given the interaction of digital design with robotics.

The experiment allows for the reflection on the future of the restoration discipline in a systematic way from the point of view of theoretical reasons and in a technical way with the realization on a 1:1 scale of a technology unit in a low-risk context. The realization served to promote a culture of a simulated industrialized restoration project, where the robots were able to perform repetitions but without the limits imposed by standardization and modularity. The amount of data at the service of the restoration process facilitates the predictability for minimizing intervention risk. The heuristic optimization represents the corrections that a craftsperson would have made to a physical model to try new solutions and discard the less effective ones: "artisans of pre-industrial times [...] did not use mathematics to predict the behavior of the structures they made. When they had talent they learned intuitively, by trial and error, by making and breaking as many samples as possible. So do we today, using iterative digital simulations" indeed "design is a predictive tool, it models something before it happens" (Carpo, 2017). The integration of robots with this information allows for the establishment of a designer-machine dialogue that enriches the workforce experience and translates it into digital data, useful for a subsequent interaction, or to expand the collective knowledge. The possibility of generating a production process based on mutual learning and information exchange is a scenario in which the architect uses design elements derived from experience and knowledge of design theory, while the machine suggests technical and performance optimizations derived from the implementation of analytic algorithms.

The design outcome image results from the extrusion toolpath and is an identifying sign of the methodology that creates it. This toolpath can be viewed as a positive expression of the dialogue that can occur between production technology and historical good. The file containing the toolpath needed to drive the kinematics has been uploaded online in the webmodel.space/woodwardchurch platform. This is a first act of dissemination of the results toward the definition of an open source database of algorithms for restoration, flexible and adaptable based on the parameters that constitute them. Not only is the geometric data shared but also the information to translate it into physical reality.

8.5.1 Limitations

The main limitation of the experiment was the lack of cases already realized that could be used as feedback for technical requests and cultural appropriation by the users of historical assets. The methodology must still be tried, tested, and directed towards the optimization of resources. Upstream of this work, it is necessary to understand the incidence of each single action in terms of investments and the balance of expenditure, depending on the type of intervention, between the technical equipment and the skilled labor. The setting hierarchy on which to research should follow the logic:

- advance laboratory experimentation, to strengthen the technical-cultural demands and the skills needed to scale-up the operating methodology;
- define the communicability between the robots on-site in the early cases for the diagnostic and survey phases;
- carry out the first tests on-site of customized production on minor heritage sites;
- apply the operational methodology on cultural heritage as an innovation measure of the overall restoration site.

8.5.2 Potentials

One of the aspects concerning robotic interventions of the built environment concerns the management of the architectural image of the product element. In this case the toolpath is considered as a geometric element that generates the form and indicator of the kinematics. The display of horizontal layers clearly recalls the additive manufacturing method for completing and readability of the architectural unit. The potential of the robot allows for control of the proportion of the layers with respect to the volume to be realized, the resolution of the extrusion, the pattern of the exposed surface, and any internal structural elements.

robotic means. One such example is that of Branch Technologies in the US where they are creating a material matrix of either plastic or carbon fibre to create a structural material scaffold for supporting a second lighter material like expanding foam.

5 In this regard, it is recalled that for the continuation of the construction of the Sagrada Familia, various boundary conditions have meant that cast stones are used in the post of the natural flood arising from the quarries near Barcelona. The quantity of material that would be necessary for the project's final flow rate and the cost component meant that it was operated with a material that was different from the historical one but compatible and with similar chemical-physical properties.

The layers represent a tool that creates a relationship between the geometry and the direction of the tooling. Tool marks can have different meanings, if critically observed. Each carved surface carries the history of its tools, although with rigid materials such as stone and wood it is possible that they are sanded and finished. Tool marks can represent a vestige of the means of making, in others they are emphasized in an attempt to make a surface plot explicit. In ancient Greece the scraping of tree trunks was presented symbolically via the flutes of columns.[6] In contemporary practice the toolpaths commonly appear as signs left by the processing of objects from larger pieces of material following subtractive processing. (Clifford, 2012).[7] Moreover, "tool marks bear the scars of the technique by which it was made" (Ingold, 2013), involving successive actions, for instance, on an original core. Tool marks inform the craft process and the understanding of an artifact.

For the architectural heritage project, the metaproject assumes significant importance. It requires organizing the input data in a hierarchical way so as to be able to clearly define the project objectives. Through the experiment the introduction of a hybrid manufacturing process was carried out using malleable material. This process has the potential to be explored, especially with regard to construction site logistics. The use of fast-curing materials allows the expressive freedom of wet construction technologies, but without the scaffolding superstructure with consequent hardening period. Digital workflow also focuses on the delocalization of the production process, which can occur in different production units, since each phase is linked to the others through a digital grammar.

8.5.3 Discussion on future developments

For the recovery of the architectural heritage, the accuracy of work tools and materials compatible with existing buildings will be very important in the future. This accuracy allows the restoration specialist to develop a technological awareness with respect to the constant evolution of materials and construction technologies. Robots may be increasingly able to operate in inaccessible and dangerous contexts and speed up the operational phases.

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-high	**Low**-medium-high	Low-medium-**high**	Low-medium-**high**

In addition to chemical-physical and aesthetic compatibility, it is possible to consider the ways in which a given material might be more convenient to use.[8] That is the decision to make if the production or

6 Fluting and reeding: https://www.britannica.com/technology/fluting-and-reeding.

7 Brandon Clifford, professor at MIT (http://www.matterdesignstudio.com/brandon-clifford) uses the Hotel Carnevalet in Paris as a case in point where the surfaces are chiseled in an inverted pyramid pattern. In the quoted paper, he states: "tool marks don't always have to imply movement over a surface. Rather, contemporary tools allow for the explicit control over tool entry, engage, and withdrawal motions".

8 The success of a material extrusion operation in restoration consists in correctly calibrating the quality and quantity of the material to maintain equivalent levels of stiffness and ductility. The use of FRP (Fiber Reinforced Polymers), with carbon, aramid or glass, during the extrusion phase could, depending on the desired elastic mod-

assembly of its minimum units is more effective than on-site, prefab on-site, or off-site.The decision may also depend on the type and size of the units to be produced. If a piece is very large or complex, it may have to be prepared in several parts and therefore its final mechanical characteristics especially in the places of junction between the parts will have to be fully understood. The advantage of working with digital data will allow for the management of variable property materials in the future, whose behavior can be predictively controlled. Unlike pre-industrial artisans, who "did not have much choice: they had to make do with whatever natural materials they could find" (Carpo, 2017).[9]

The operational phases are assumed to take place in an integrated manner with integrated tools designed to collaborate with the human workforce. During the experiment there were few interactions with the robot, usually carried out to adjust the speed of execution of some phases through manual controllers. It is possible to foresee a scenario in which the robots will be able to share the professional's work space, to understand their characteristics and to perform operations not as simple performers but as intelligent assistants.

This cobotic approach diverges from its segregated use in the existing industrial production chain. In this scenario the robots not only perform repetitive actions that require supervision but take part in the project by interacting with real-time feedback where the calculation algorithms are able to suggest optimizations, from kinematics, to the use of material resources, to the organization of site. These cobots (Peshkin and Colgate, 1999) will have the cognitive ability to develop a human-machine system (Daugherty and Wilson, 2018), in which the robot collaborates to extend the skills of the designer whose creative aptitude contributes to proposing new processes, not limiting oneself to mere automation. This process is an expression of the digital culture in the area of buildings and the restoration of monuments through a new material sensibility.

ulus, lead to restorative stiffness, or increase the ability to withstand high deformations, hysteretic cycles, or even amortize the seismic waves. These polymers, to ensure reversibility, can be eliminated by heat, electromagnetic vibrations or solvents. It will also be necessary to take into account the strong anisotropy component of the printed material by layers which differs substantially from the material cast in a mold with isotropy quality. However, the most advanced 3D printing processes are able to realize any point, voxel, or volume with different mechanical characteristics. The material must not be too soft because otherwise it comes into play only when the deformations of the masonry and the fractures have already formed beyond repair. On the contrary, if it is too rigid it could break when it will no longer hold itself, even before the wall facing. The masonry, among other things, tends to break first due to deformation (displacement) and excessive loads. In the specific case of polymers suitable for being extruded, it is not a matter of conventionally regulated materials in the structural field, the utmost attention must also be paid to resistance tests to obtain reliable data in the conditions of application in a first phase in the field of scientific research. It must be taken into consideration that the environmental conditions in which the printing takes place can vary the mechanical characteristics of the final product. However, the principle is still valid that the new insert should be either weaker or stronger than the mechanical characteristics of the existing insertion context for load-bearing structures.

9 in "The Second Digital Turn" (2017), Mario Carpo describes this idea with the example: "no artisan would x-ray a piece of timber before working on it, but all good artisans would know how to make the best of whatever they find in it when they start carving it".

8.6 Final feedback: exploiting the Fourth Industrial Revolution

Evaluation of the experiment provides insights for alternative scenarios for the development of the proposed methodology. The different scenarios could depend on how work groups are organized to complete a project, for which the contribution of a material specialist or data scientist may be more relevant. Alternate scenarios may depend on the way in which research centers want to tackle the issue, even if only by focusing on the development and resolution of technical aspects.

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-high	**Low**-medium-high	**Low**-medium-high	**Low**-medium-high

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-**high**	Low-**medium**-high	Low-**medium**-high	**Low**-medium-high

Expertise	*Labor*	*Equipment*	*Material*
Low-**medium**-high	**Low**-medium-high	Low-medium-**high**	Low-**medium**-high

Expertise	*Labor*	*Equipment*	*Material*
Low-medium-high	**Low**-medium-high	Low-medium-**high**	Low-medium-**high**

In this research, the concept test was carried out in a low-investment manner, carrying out the simulation of a process for which:

- a pre-owned robot was used with not particularly advanced mechatronic technology. Other sectors will be able to make investments more accessible while the TRL advances;
- we will act in a pioneering way, so any attempt at applicability to the architectural scale will constitute a datapoint to which to refer for further applications.

It is foreseeable the possibility to carry out interim, low cost, realization of the workflow. That is, it will be possible to proceed gradually with the implementation of the technology before reaching increasingly high levels of sophistication.

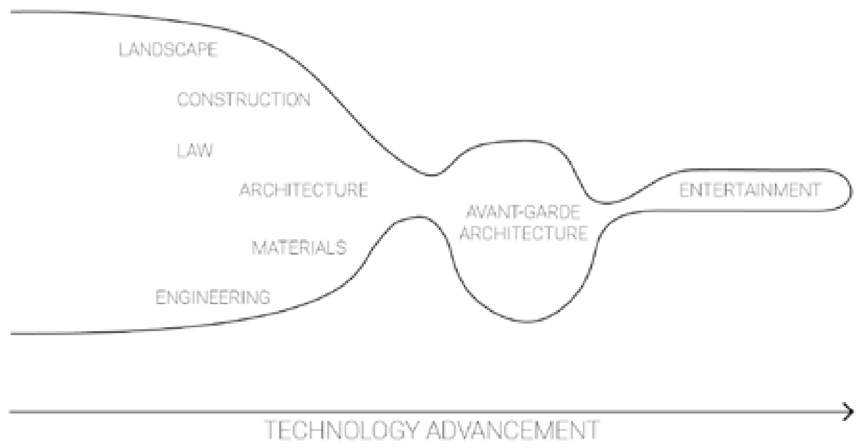
A clear example of this technological condition is the fact that a stationary robot was used for the experiment, not defined as a mobile platform in space. The design in this type of workcell makes it possible to decide the design "zero" for each workcell. At the end of the work, for example in 3D printing, the robot could be raised or moved to another fixed position by redefining the workcell and repositioning the zero. This methodology requires phasing the construction by dividing the three-dimensional space into work spaces. This could be an intermediate research step in which it will be possible to optimize some phases of the process (such as cleaning or consolidation of damaged areas in undercuts) working more on scripting and not necessarily making use of the most advanced and expensive hardware. Ultimately, applied research allowed for a number of areas for future development and identification of potential blind-spots.

There are various elements of analysis that suggest that the use of robots on the construction site for building interventions can occur in the near future, possibly in less than a decade (Fig. 8.8, Fig. 8.9). An initial consideration for robots in construction will be the management of the digital project and parsing work into different phases or locations. As evidenced by the Sagrada Familia project, the start of production of components began simultaneously in several production stations. This scenario can be either on-site or off-site. In special time-sensitive situations, the need to accelerate production and operate with a just-in-time strategy can be defined (Burry, 2016), so that various components arrive at the site from different production sites.

The management of new and scaled-up tools-workflows-technologies will be up to an operator (Fig. 8.10) able to:

- **understand the dynamics of digital complexity;**
- **modify the operational sequences of work flows and verify optimization opportunities;**
- **synthesize the various collaborative technologies emerging in Industry 4.0**
- **balance the technical-theoretical contribution in a project;**
- **organize work groups and collaboration.**

This Fourth Industrial Revolution operator will be a synthetic figure among all the experts to be involved. This operator will possess high-level knowledge allowing them to both understand and manage at what time to change-replace-integrate technologies in future business models. The outcome may provide benefits in time, scope, quality, and finances. With the above premises, the architecture discipline will become a driving force for other sectors, as it is the perfect synthesis between theory-practice-culture-social organization and work.



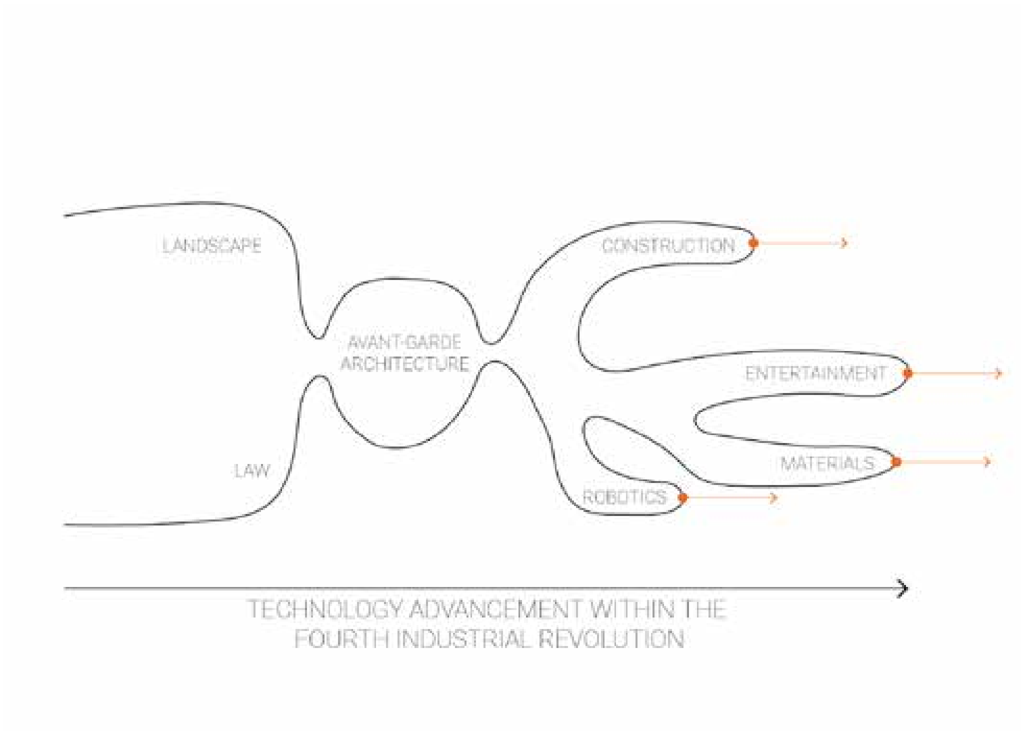


Fig. 8.8 Leading sectors in the development of digital technology. The architecture uses tools from the entertainment industry for the production of the design work and for project communication. Following, the sectors for which the use of technology is not the main driver of development.

Fig. 8.9 With the Fourth Industrial Revolution, technological progress will be driven by robotics and automation, with repercussions on a wide range of sectors. This is an opportunity for the construction industry to finally move forward from the methods of the past.

Fig. 8.10 The overlapping of the skills of the professional able to manage the digital complexity with the information of automatic processes, generates the figure of the Operator of the Fourth Industrial Revolution.

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PART V - CONCLUSIONS

9 Feedback on workflows within the Fourth Industrial Revolution

ABSTRACT

The case study analysis derived from Architectural Heritage conservation and robotic production led to a narrowing of the subject until it converged into an experiment. The wide range of elements was restricted to a limited - time applied research activity, which served to expand the discussion towards critical speculation informed by the experiment.

After having examined the results of the work carried out, it was possible to affirm that, already starting from the academic environment, there were the theoretical and technical presuppositions to develop the proposed methodology on a larger scale than solely that of the laboratory. It was, therefore, demonstrated that it is possible to widen the conversation with the construction industry and with Digital Heritage specialists, in order to expand the expertise of architects, who potentially will become the prime operators of the Fourth Industrial Revolution.

The elaboration of the state of the art in robotics for architecture has allowed for an understanding of how academic research is increasingly approaching construction, material science, and new technologies to favor the transition to on-site prototyping of building elements. In order for a transition from a prototype (MVP) workflow to a real (construction 4.0) workflow to occur, it will be necessary for research centers to focus on solving practical problems in the construction sector. Process and product innovations, from design to construction, and the results of research that will advance the various technological TRLs to encourage investment and accelerate technology transfer from the academy to professional practice.

This research advocates the importance of the study from an educational perspective. Soon, designers will need new skills and new approaches to architectural practice. Higher education has an impactful role in preparing future professionals. Teaching in preparation for the Fourth Industrial Revolution means educating designers who will have a fundamental role in projects as master-builders. Process information will also establish a link between actors and project phases that are commonly distinguished as designers, construction industry, owners, and occupants that will operate as data - enabled project teams.

Keywords: *Research Feedback, Digital Workflows, Design Process, Construction Industry, Future skills*

9.1 Implications of the applied research for workflows at the scale of architecture

"It is a well known pattern in the history of technological change that new and potentially disruptive technologies are often first tasked to emulate pre existing ones [Mario Carpo, 2011]

This thesis has taken the opportunity to redefine the design and operational work that exists within Cultural Heritage work. Case studies in Cultural Heritage and technology were used to identify key tools that might positively impact the on-site operations of restoration sites. The resulting experiment studied the potential transfer and integration of these tools in a customized workflow through a 1:1 architectural scale. A prototyped workflow was defined with the intention of operating at the borders of different disciplinary fields and integrating aspects of the design process that were previously considered fragmented in the First Digital Age. The project materialization took place through the use of digital manufacturing technologies to expand and customize the range of possible on-site operations. The results demonstrated both the reliability and the potential of such a laboratory environment. University research environments and digital fabrication labs (fab-labs) in particular can make a contribution to the industrial development of the sector, advancing research in a low-risk, non-industrial context.

The experimental workflow, as carried out, brought together robots and architectural systems and introduced a series of design tools related to computational and digital fabrication processes. The experiment included various tools and technologies in the early stage of the design of architectural units, organisms, or systems, in order to guarantee efficiency in the phases of manufacture, assembly, or installation of the components. The described process for a pre-existing volumetric context passes from the project to the manufacturing, transforming the digital bits into the physical.

The workflow operates as a hybrid space between the designer and the machine, in order to create a new manufacturing process by stimulating creativity and at the same time simplifying complex geometries into simple geometric elements. This potential workflow should be interpreted as a methodological prototype (Fig. 9.1) worthy of refinement in future research environments. It favored the development of technological thoughts that will benefit the construction sector in the coming decades. The cognitive aspect and the ability to manage the phases of the process constitute the most industrially marketable element of this dissertation. The process consists of the systemization of all the technical and theoretical elements that have given shape to the concept test.

In this case, the theoretical formulation also concerned the efficient use of material resources, through the additive construction methodology. This methodology allows for the composition of geometric elements in relation to the degrees of freedom of movement that the robot offers. Through the integration of both algorithms for the robot and parameters for the geometry, the material characteristics and construction sequences are managed. Furthermore, the use of a low-engineered material such as clay, although used only for the purpose of the concept test, allowed for the speculation about the future reintroduction of vernacular materials for sustainable design throughout the entire life cycle of buildings. This concept linked to the Architectural Heritage implies the design of reversible, eco-compatible, and recyclable technological units.

The research informs future developments that must be taken into account in the monitoring of the works carried out, especially when it comes to new generation materials that are not yet experienced in the construction sector. It will be necessary to define quantitative analysis methods on the performance of materials, on the impact related to gray energy, and on the actual economic benefits deriving from the adoption of industrial robots in architectural construction. Quantitative feedback analysis will be essential to operate in a predictive design environment. Unlike standardized, static, and homogeneous industrial materials deployed in mass production, in the future, designers will be able to work with variable property materials perfectly described with digital data that will allow them to predict behavior and transformations over time.

It's possible

The case study analysis derived from Architectural Heritage conservation systems and robotic production tools led to a narrowing of the subject until it converged into an experiment. The wide range of elements in the introduction has been restricted to a limited-time, applied experimental activity which then served to expand the discussion towards critical speculation informed by the experiment. At this point, after having examined the results of the work carried out at the LTU - CoAD, it was possible to affirm that, already starting from the academic environment, there were the theoretical and technical presuppositions to develop the proposed methodology on a larger scale than simply that of the laboratory. It has therefore been demonstrated that it is possible to widen the conversation with the construction industry and with Digital Heritage specialists, in order to strengthen investments in the field and expand the expertise of architects. Architects stand to potentially become the prime operators of the Fourth Industrial Revolution.

It's necessary

This research was undertaken while certain broader trends occurred that different research institutes are projecting to take place in the coming decades. The fundamental points that one should take into consideration are:

- the impact of the early stage phases of architectural design;
- the spread of robots in the production sector and the consequent reduction of their market price;

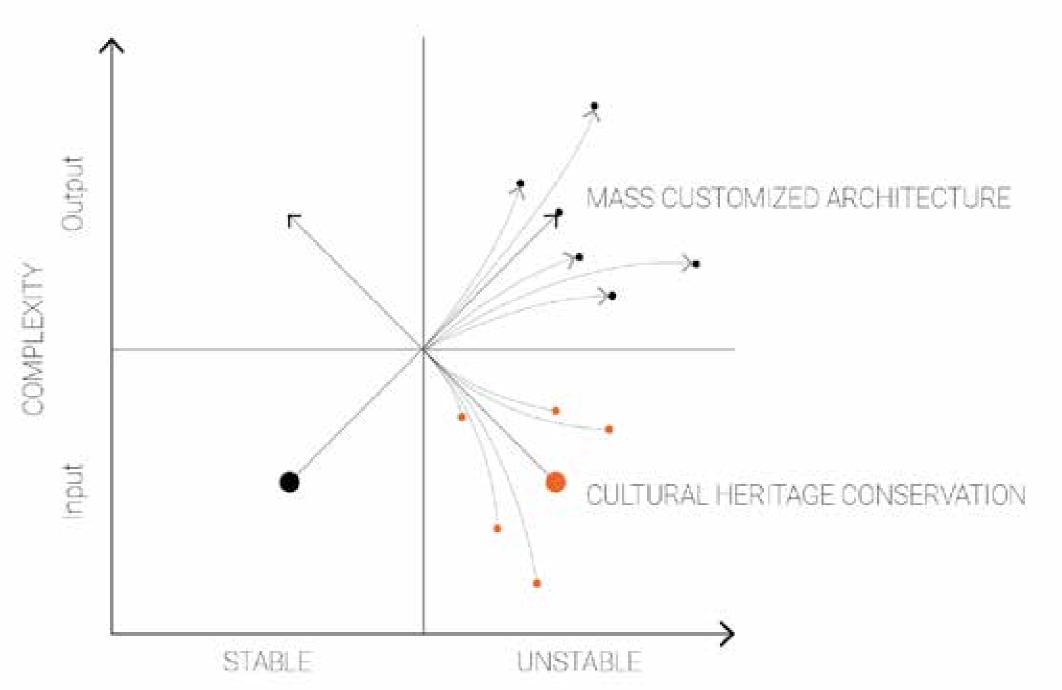


Fig. 9.1 The diagram summarizes the concept of mass customization from two different applications. In architectural design, mass customization is delivered after collecting "stable" inputs from the clients, who seek for adaptation of living standards for personal needs. In Cultural Heritage conservation, it's the other way around. The design input comes from damaged buildings that require case-by-case analysis and recovery applications. The wide range of options, due to unpredictability of the de facto stated of buildings, makes the input an "unstable" issue. In conservation, the objective of mass customization is to reintegrate a building and perpetuate its value in the future.

- the increasing cost of labor on the construction site, which represents a determining factor in the field of Architectural Heritage recovery, which is a delicate and careful work (Heritage labor is a premium).

Early stage parametric design

Digital design allows for the integration of the early stage analysis, with the generation of form, and the deployment of respective production methods. This process is guided by a data richness that accompanies the design from the early stage to the executive phase, within a single workflow. With the Second Digital Turn, the quantity of input data for each project grows exponentially and this allows for the control of the data stream in a predictive manner through the use of later stage simulation tools. The digital simulation consists of the visualization, through a digital graphic interface, of the dynamic phenomena that contribute to the construction of the architecture.[1] This technical possibility of connecting design and construction makes it possible to optimize the design reality for which the longer you wait to make design changes, the more expensive the change becomes. A visualization of this concept is represented by the MacLeamy curve (Fig. 9.2), which shows the impact that the decision-making process is able to determine in terms of costs and overall performance of an architectural product. The critical process that follows the theorization of this cost results in suggesting the front loading of the design efforts to reduce the cost of late design changes. For this purpose, information on the design process is useful, it allows designers to maximize the impact of the choices made in the conceptual phase and reduce the costs of their application.

Robots ubiquity and manual labor fall

In 1998, James Keramas set up several trends he was analyzing in the US market for robot adoption in the manufacturing sector. From the first mass production experiments in the automotive industry until the publication of the text Robot Technology Fundamentals, there was a 50% drop (including inflation in the calculation) of the price of the robots (Tab.1), exactly inverse-proportional to the increased quality and life expectancy (Fig. 9.3). Market dynamics, again in the 1960s until the 2000s time window, also highlighted how the cost of human workforce in the automotive industry itself rose sharply. An increase also occurred in the operational cost of the robots, but mainly depended on the natural increase in the cost of the resources necessary for the management of a plant for mass production. These same trends have been confirmed by the IRF (International Robot Federation) that resumed the analysis starting in the 1990's and continuing to present day (Fig. 9.4). The same demand-supply price dynamics (hourly cost of human operator in manufacturing) are also attributable in the European context (Fig. 9.5), and in particular to the leading economies such as Germany and France.

The accessibility of robots has led to greater investments in the development of mechatronic technology, software, and network technologies for their installation and use, and consequently

1 These methodologies derive from the automotive and the naval industry.

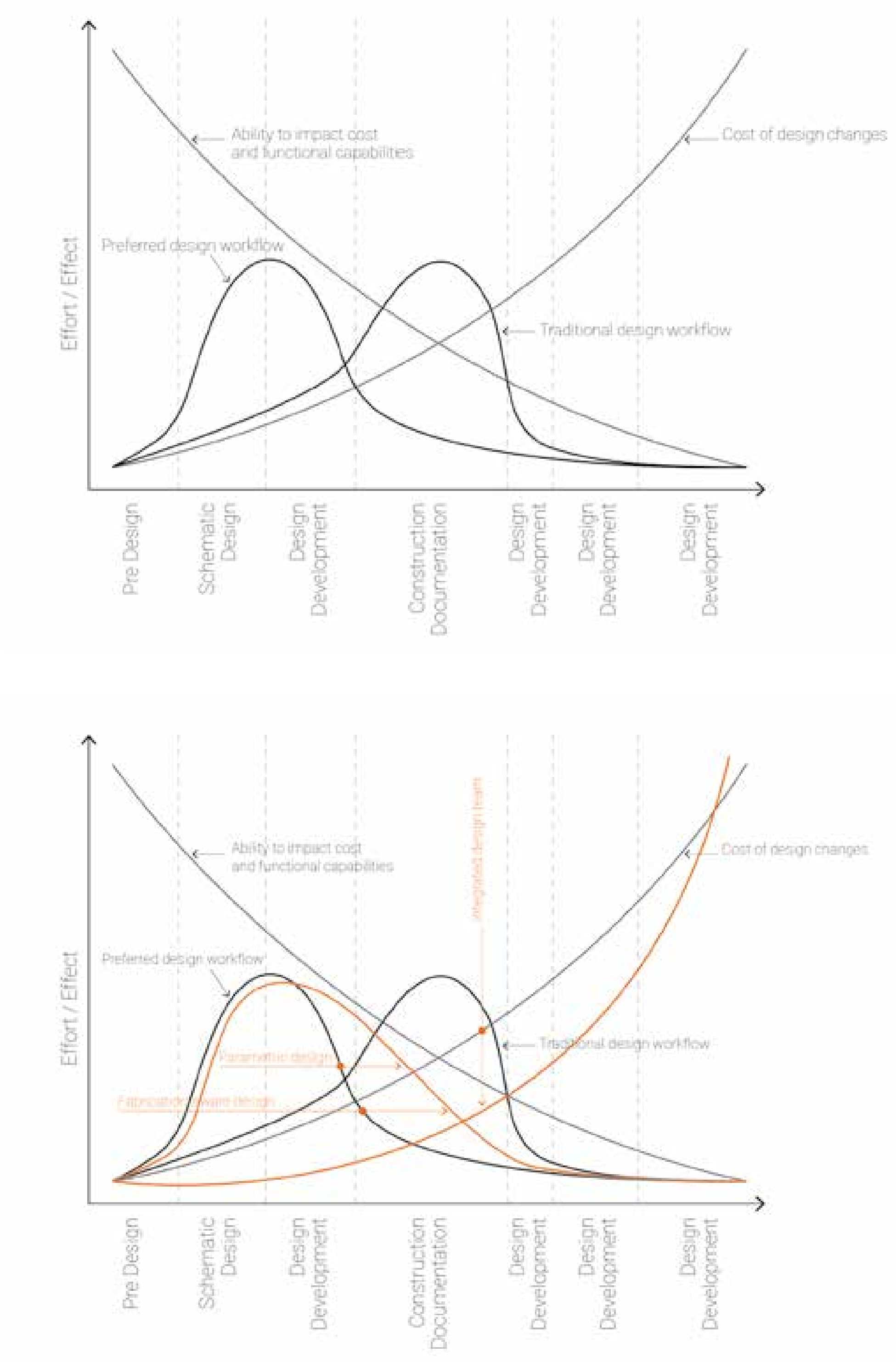
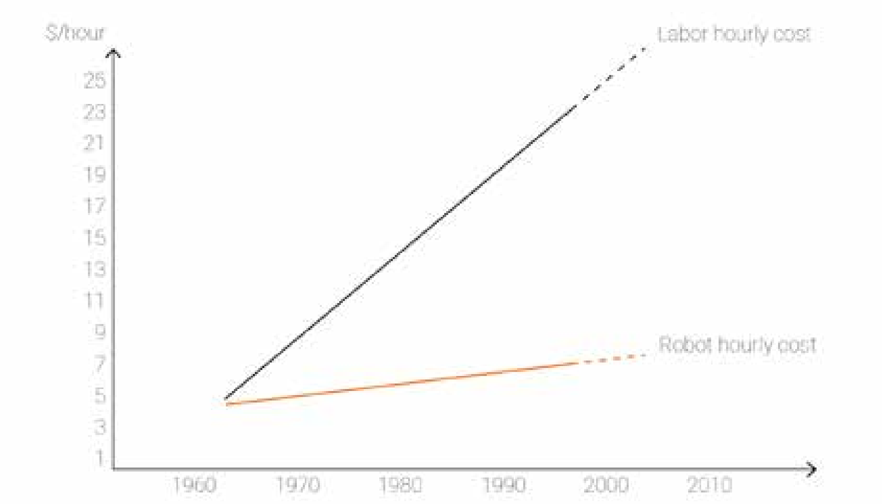


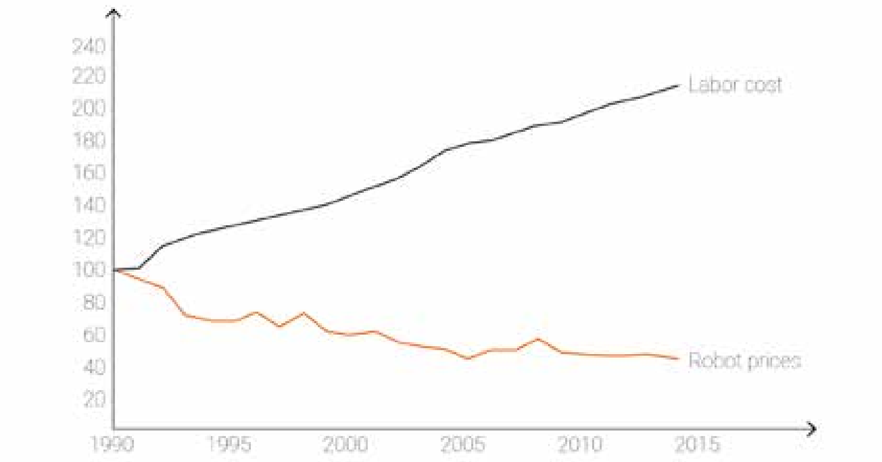
Fig. 9.2 The MacLeamy Curve, by Patrick MacLeamy. It is based on the observation that the design effort in architectural projects should be shifted earlier in the process to reduce the impact of design changes. The early stage of design has a strong influence on the result, with a low impact on cost. The dissertation advocates for the possibility of shifting the design phase forward and extend the project elaboration, to achieve higher building quality. This process is made possible by the tools of the Fourth Industrial Revolution, that integrate design and production through the parametric and fabrication-aware design. Source: https://www.danieldavis.com/macleamy/.

has increased the number of robots in manufacturing processes.[2] On a global scale, in 2016 it was recorded that for every 10,000 employees there were 85 robots installed in the manufacturing industry[3] (Tab. 9.2) The data concerning the increasing quality of robots (Fig. 9.6) and their durability over time suggests that they can be transferred from a sector in which automation investments are already high, with growing sectors. It is likely that the construction industry can absorb used robots, for example by the automotive industry. This will give accessible less expensive tools and less investment, at least at an early stage, in order to optimize processes and workflows that combine digital design and customized fabrication.

The European framework program Horizon2020, which is nearing its conclusion, has left ample room for research on robotics. Market indicators suggest that more attention will be paid to the development of automation in the construction sector in the next research investment program. In Europe, it is estimated that by 2030 in a baseline scenario, there will be a reduction of the workforce of 13.000 people, while in an accelerated digitalization scenario an increased loss of 57.000 people (Fig. 9.8). The loss of workforce in the construction market was evident, particularly with the global recession in 2008. "One of the biggest threats to the labor-driven industry is the growing shortage of workers". Returning to the United States, "600,000 workers left construction jobs in 2008 never to return".[4] The construction site is the place where workers do not want to return, as perceived as dangerous, dull, difficult, and dirty.[5] The characteristics they define are recognized in the 4Ds jobs. Robots also come to help in the contexts of the 4Hs jobs: hot, heavy, hazardous, and humble. The lack of workforce, the increased cost of skilled labor in manufacturing, and the ubiquity of robots (Fig. 9.9) due to the reduction in technology prices will be the fundamental elements (Fig. 9.7) that will lead to a profound change in the construction sector in the next decade.

2 "While sensors and actuators once had to be individually connected to robot controllers with dedicated wiring through terminal racks, connectors, and junction boxes, they now use plug-and-play technologies in which components can be connected using simpler network wiring. The components will identify themselves automatically to the control system, greatly reducing setup time. These sensors and actuators can also monitor themselves and report their status to the control system, to aid process control and collect data for maintenance, and for continuous improvement and troubleshooting purposes. Other standards and network technologies make it similarly straightforward to link robots to wider production systems. Robots are getting smarter, too. Where early robots blindly followed the same path, and later iterations used lasers or vision systems to detect the orientation of parts and materials, the latest generations of robots can integrate information from multiple sensors and adapt their movements in real time. This allows them, for example, to use force feedback to mimic the skill of a craftsman in grinding, deburring, or polishing applications. They can also make use of more powerful computer technology and big data–style analysis. For instance, they can use spectral analysis to check the quality of a weld as it is being made, dramatically reducing the amount of post-manufacture inspection required". From: https://www.mckinsey.com/business-functions/operations/our-insights/automation-robotics-and-the-factory-of-the-future.
3 IFR: https://ifr.org/ifr-press-releases/news/global-industrial-robot-sales-doubled-over-the-past-five-years.
4 "The Construction Labor Shortage", in *Forbes*: https://www.forbes.com/sites/columbiabusinessschool/2019/07/31/the-construction-labor-shortage-will-developers-deploy-robotics/.
5 "Some rule-of-thumb applications for robots are the four Ds - dull, dirty, dangerous, difficult - and the four Hs - hot, heavy, hazardous, and humble. They are aimed at replacing 4D and 4H jobs". From: Keramas, J.G., Schin, T., McAvey, F. and Produced By-Main, L., 1998. *Robot Technology Fundamentals*. Delmar Learning.





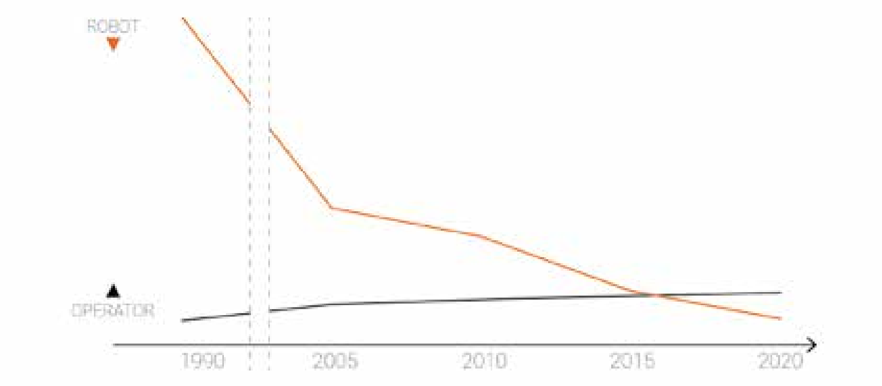


Fig. 9.3 Hourly cost of a robot versus human labor in the automotive industry. Source: Keramas, J.G., Schin, T., McAvey, F. and Produced By-Main, L., 1998. *Robot technology fundamentals*. Delmar Learning, p.5.
Fig. 9.4 Cost of automation. Index of average robot prices and labor compensation in manufacturing in United States, 1990 = 100%. Source: Economist Intelligence Unit, IMB, Institut fur Arbeitsmarkt und Berufsforschung, IRF, US Social Security data, McKinsey analysis. Available at: https://www.mckinsey.com/business-functions/operations/our-insights/automation-robotics-and-the-factory-of-the-future.
Fig. 9.5 The hourly cost of robots compared to human operators (euros/hour, France). Over time, increased productivity, the lengthening in the lifespan of solitions and the drop in equipment prices favor the move towards robotization, while labor costs continue to rise. Source: IFR, INSEE, Eurostat, Roland Berger study. Available at: Berger, R., 2016. *News| Roland Berger*, p.6.

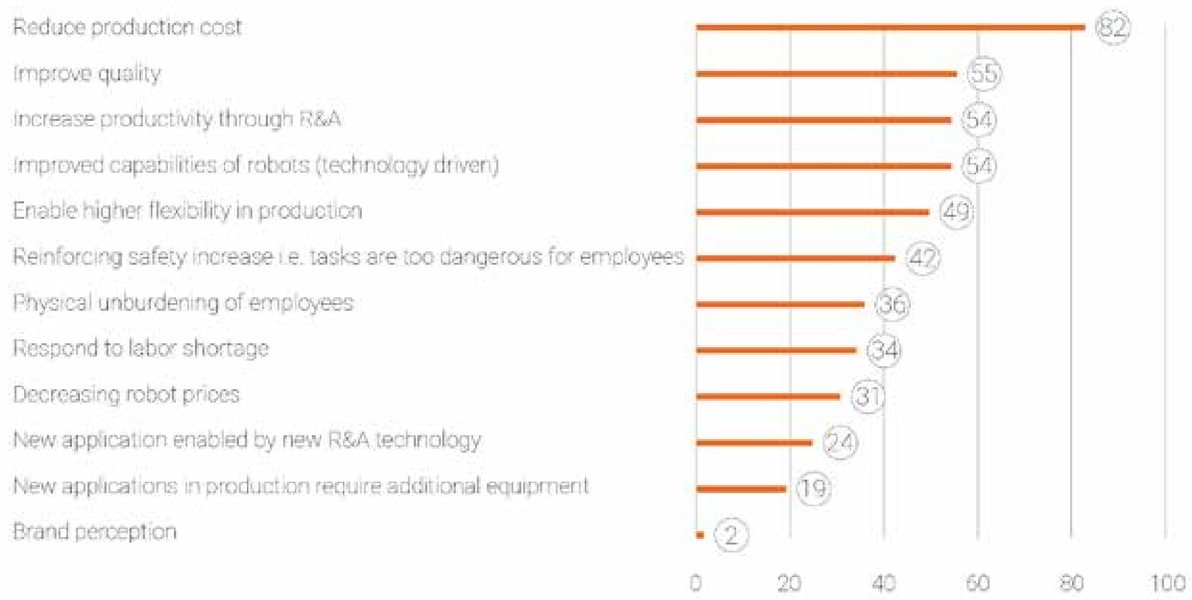
Period	Average Industrial Robot Price	Durability expectation	Operational cost/hour
1960s	25.000$ (current $210,346.27)	8 years	4$
1970s	45.000$ (current $288,794.44)	8 years	5$
1980s	60.000$ (current $181,114.17)	15 years	5,5$
2000	72.000$ (current $112,551.62)	17 years	7$

Installed industrial robots per 10.000 employees in the manufacturing industry in 2016	
South Korea	631
Singapore	488
Germany	309
Japan	303
Denmark	211
United States	189
Italy	185
Spain	160
Canada	145
France	132
Switzerland	128
Australia	83
United Kingdom	71
China	68
India	3
Average world	85

Tab. 9.1 Lowering of the cost of robots in the United States from the 1960's to the 2000's. down Source: Keramas, J.G., Schin, T., McAvey, F. and Produced By-Main, L., 1998. *Robot Technology Fundamentals*. Delmar Learning, pp.3-7.
Tab. 9.2 Source: IFR. Available at: https://www.therobotreport.com/10-automated-countries-in-the-world/.

	1975	1980	1985	1990	1995	2000	2005	2010	2015	2020
Number of axis	5	6 to 8	12		21	27			32	
Capacity - kg	6	60	90	>120				1.000		
Max reach, m	1		2					3		

[1] Allows arc welding, adhesives dispensing, machine loading
[2] Spot welding, materials handling.
[3] All application areas; right size for the task.



100% = 85 respondent

Fig. 9.6 Growth of robots on the market. Base quantity SKUs. Source: McKinsey & Company, "Automation, robotics, and the factory of the future". Available at: https://www.mckinsey.com/business-functions/operations/our-insights/automation-robotics-and-the-factory-of-the-future.
Fig. 9.7 Main drivers triggering investment in robotics and automation solutions. Source: McKinsey Global Robotics Survey 2018.

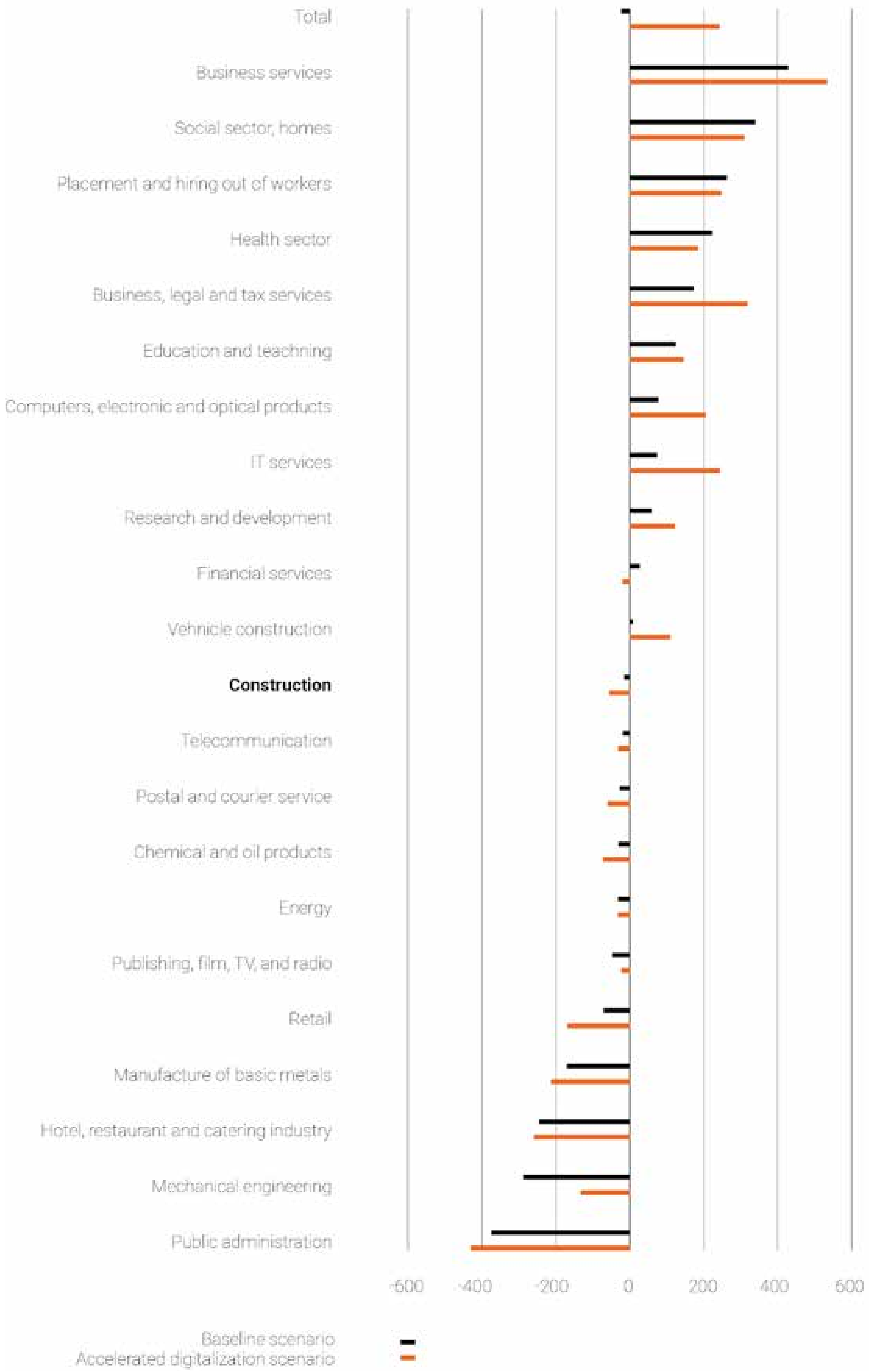


Fig. 9.8 Labor market forecast. Changes in employment in selected sectors 2014-2030 in 1.000s. Source: Nahles, A., 2015. *Reimagining Work 4.0 green paper*, p.52.

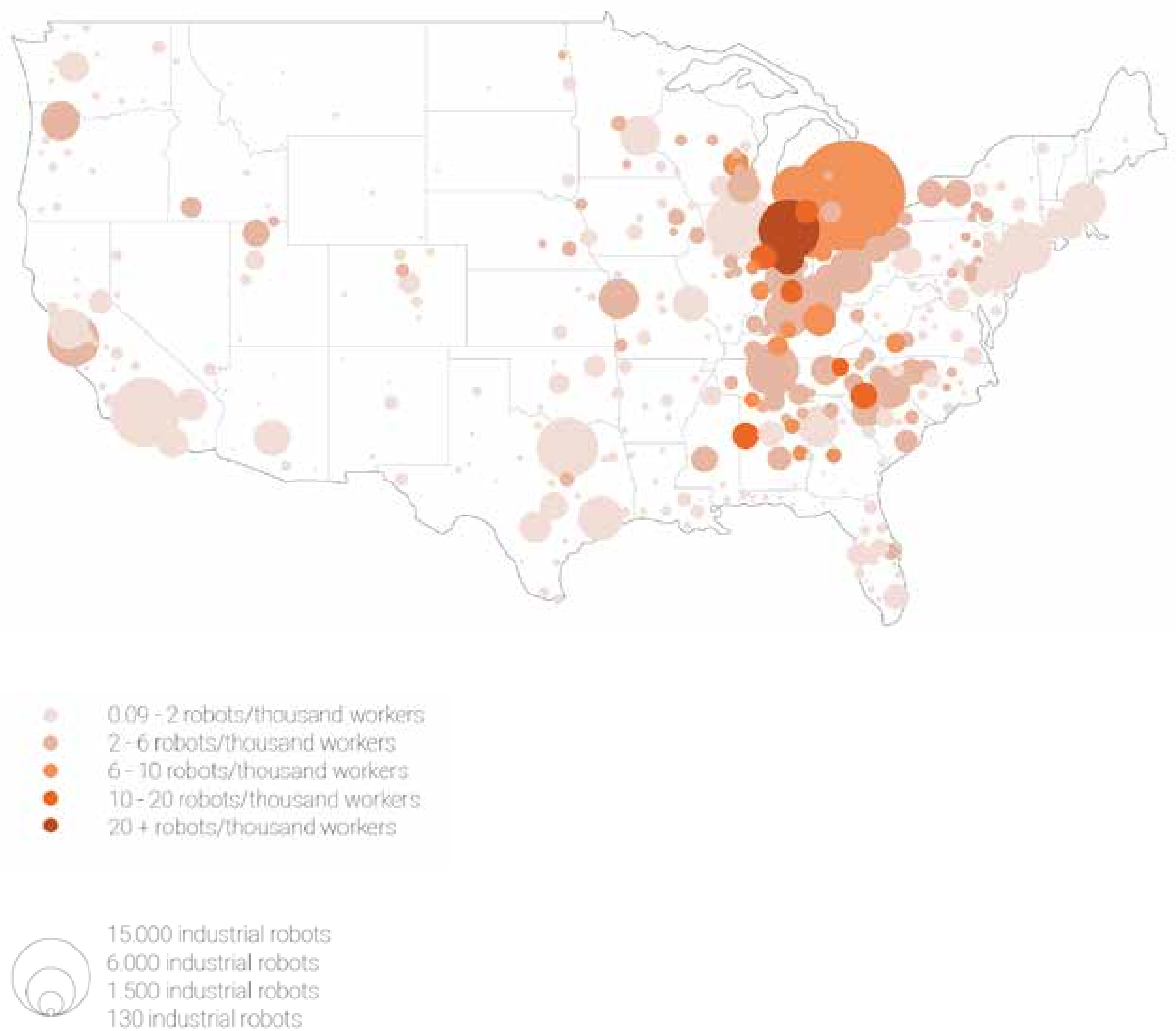


Fig. 9.9 Where robots are in the United States. According to the data, industrial robots in the country are 233,305. Michigan, where the auto industry is concentrated, accounts 28.000. It is 12% of the national total. Metro Detroit, an "auto-intense" area, has 15.000 robots in place or 8,5 every 1000 workers, three times more than in any other metros in the country. Robots are mainly used for welding, car painting, product assembling, materials handling, and packaging. The number of robots in operation increased significantly during the post-crisis auto boom between 2010 and 2015. The experimental phase of this dissertation was developed in Detroit. It is one of the cities with the highest concentration of robots in the world. Through direct experience gained during the development of the research, it was assessed that manufacturing industries are currently interested in interacting with the higher education sector to broaden the range of automation applications, from mass production to building construction. Source: Brookings analysis of the International Federation on Robotics data. Available at: https://www.brookings.edu/blog/the-avenue/2017/08/14/where-the-robots-are/.

9.2 Comparison of workflows: analysis, design, fabrication, and construction

Before starting the experimental phase, an a priori hypothesis was formulated to define the operations to be performed in the laboratory. This hypothesis was compared with expertise - labor - equipment - materials involved in the research project. This working method allowed for the broadening of the discussion on the topic through a comparison between the hypothesis (based only on theoretical knowledge), experimentation (based on knowledge gained through DIY strategy), and future experimentation (on the basis of the analytical tools acquired for the understanding of upcoming trends). The same comparison made it possible to highlight clearly what level of expertise was necessary to achieve the objectives. A summary table (Tab. 9.3) highlights the main aspects that distinguish the three working methods, only one of which has been carried out through the experiment and is therefore used as a reference to test the other two. To make them consistent and comparable the workflows (Fig. 9.10) have been divided into major categories of analysis - design - fabrication - construction.

A macro-scale analysis allows for the definition of how the workflows have different degrees of flexibility, fluidity, and enrichment of data between one phase and another. WF1 (hypothesis) is more rigid, as its formulation occurred at a time of research in which the principal investigator had not yet been exposed to the practical principles of data driven design, the flexibility of robotic work tools, and large-scale digital fabrication. From this perspective, WF1 results in an operational structure that still suffers from a certain rigidity and sequentiality. WF2 (MVP) sees the potential for greater interoperability in the use and simulation of digital data, which can then be seen when all the necessary skills interact in the same digital workspace, to give rise to WF3 (future).

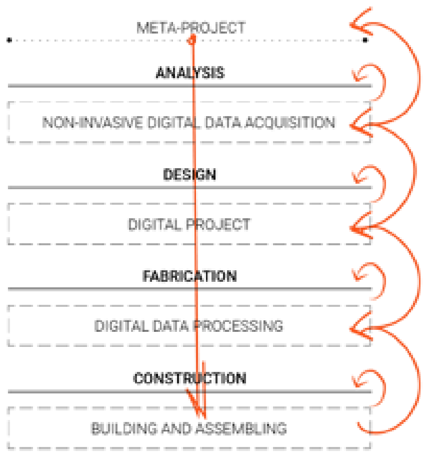
Among the three different workflows, there was also a strong desire to integrate the skills involved in the process, which required the incorporation of both tools and software. The education of the role of the architect-operator of the Fourth Industrial Revolution will be better prepared when highered includes these types of topics early in the university curriculum, not leaving them relegated to fields of specialization. Upstream of all three workflows, a metaproject constant is maintained, which initiates a space of design possibilities (De Landa, 2000) characterized by a wealth of digital data available today. This wealth of data is not used a posteriori, but on entry, as a useful means for creative exploration.

So far the discussion on workflows has taken place through an isolated vertical analysis, a progression from beginning to end. More critically, a horizontal reading can highlight the prototype experiment (MVP), through which the assumptions of the hypothesis was tested. Horizontal cross sections help to show where the experiment has helped shape some of the key aspects. Once the assumptions were processed with the hypothetical workflow (WF1), the WF2 allowed for the elaboration of a robust notion of what might be possible by optimizing the process. Although the WF2 was limited in scale, finances, and exposed the inexperience of the researchers, it created the conditions for more informed decisions for the WF3. The potential of this research consists of "thinking outside experience" (Epstein, 2019).

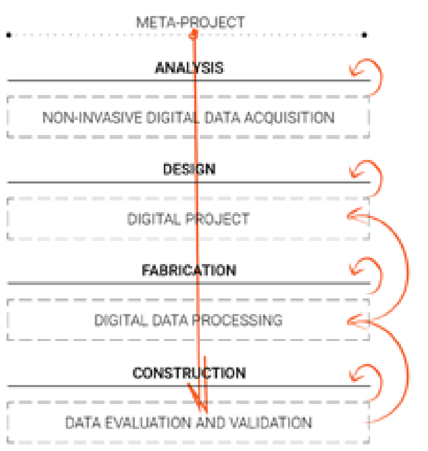
	WF1 (Hypothesis)	**WF2 (MVP)**	**WF3 (Future)**
Analysis Technological elements: ° architectural unit ° subsystem ° system	Non-invasive on-site robotics: **• diagnostic** ° thermography ° ultrasonic devices ° endoscopes **• survey** ° photogrammetry ° geometry	Non-invasive on-site analysis: **• survey** ° photogrammetry ° rpas ° tls **• geometry** ° tls ° close range	Non-invasive on-site analysis: ° diagnostic ° survey Data collection ° open source data ° digitized heritage
Design	Dynamic 3D model ° computer vision ° robot-sensing	Static 3D model ° project on ch ° toolpath ° robot-script	Dynamic 3D model ° information data ° digital twin ° IoT
Fabrication	Installation of off-the-shelf end-effectors and sensors	Mock-up for on-site simulations by using diy customized tooling (extruder, end-effector)	Smart fabrication with integrated bespoke tools
Construction	On-site prefabrication Off-site prefabrication	Indoor simulation of a on-site process	On-site making On-site prefabrication

Tab. 9.3 The table summarises the topics that are developed in the following paragraphs of the conclusions. There are two keys to interpretation. One vertical and one horizontal. The first takes into account a) hypothesis to carry out the first-hand experiment b) performed lab experiment and c) future developments of the subject. The second is thematic and concerns the phases of the proposed workflow for robotic additive manufacturing on Cultural Heritage, which is expressed as analysis, design, fabrication, and construction.

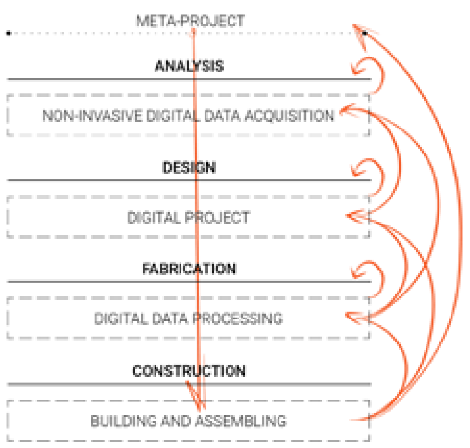
Digital Workflow - HYPOTHESIS



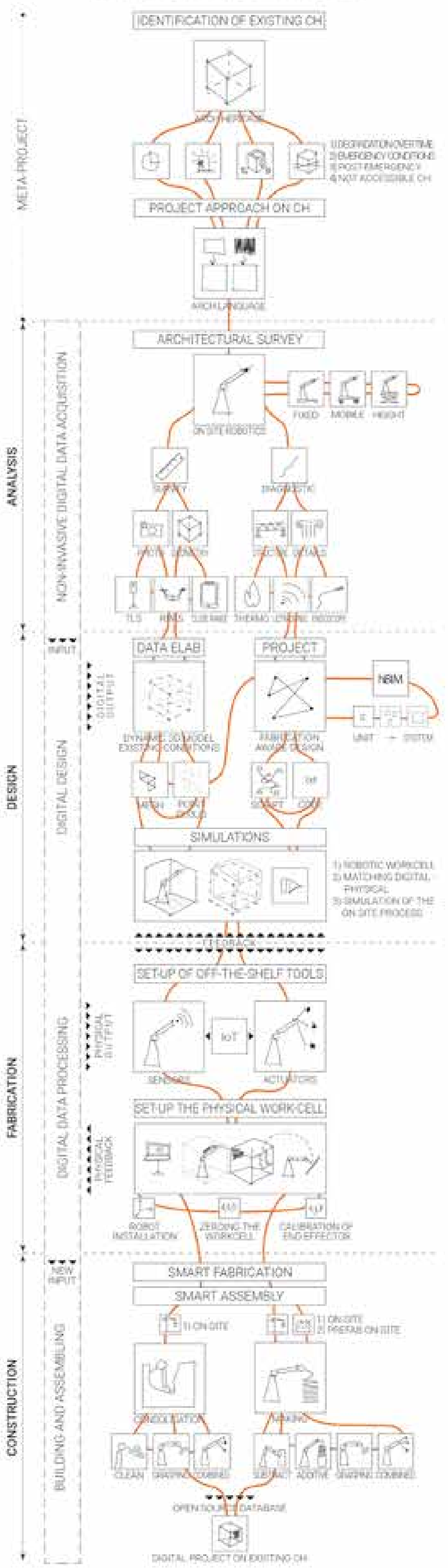
Digital Workflow - LAB EXPERIMENT



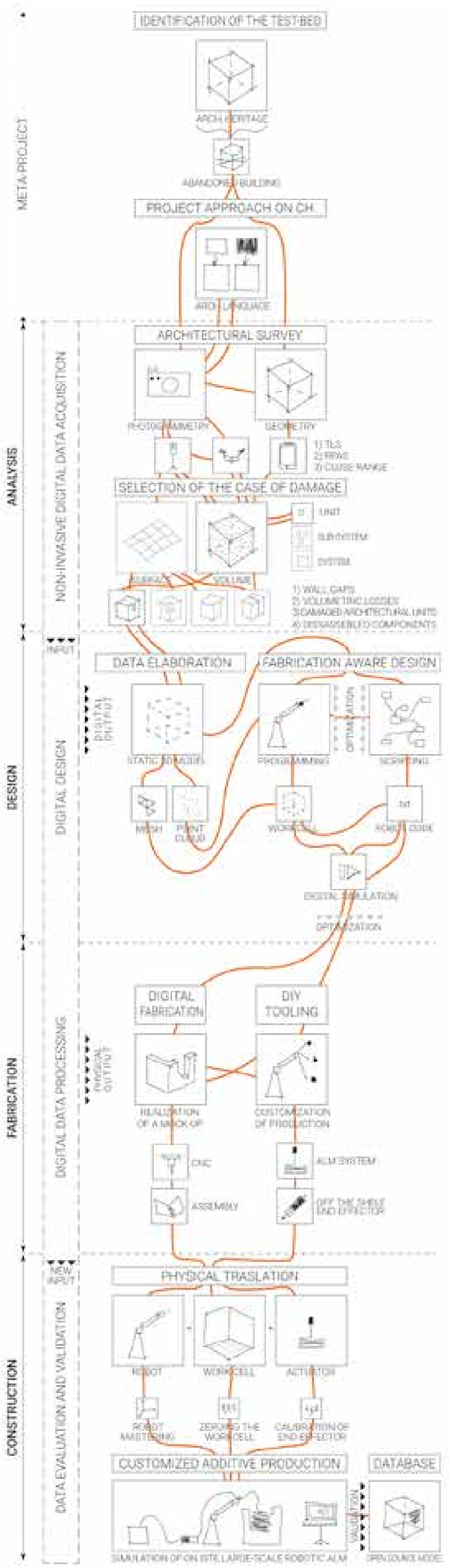
Digital Workflow - FUTURE SCENARIO



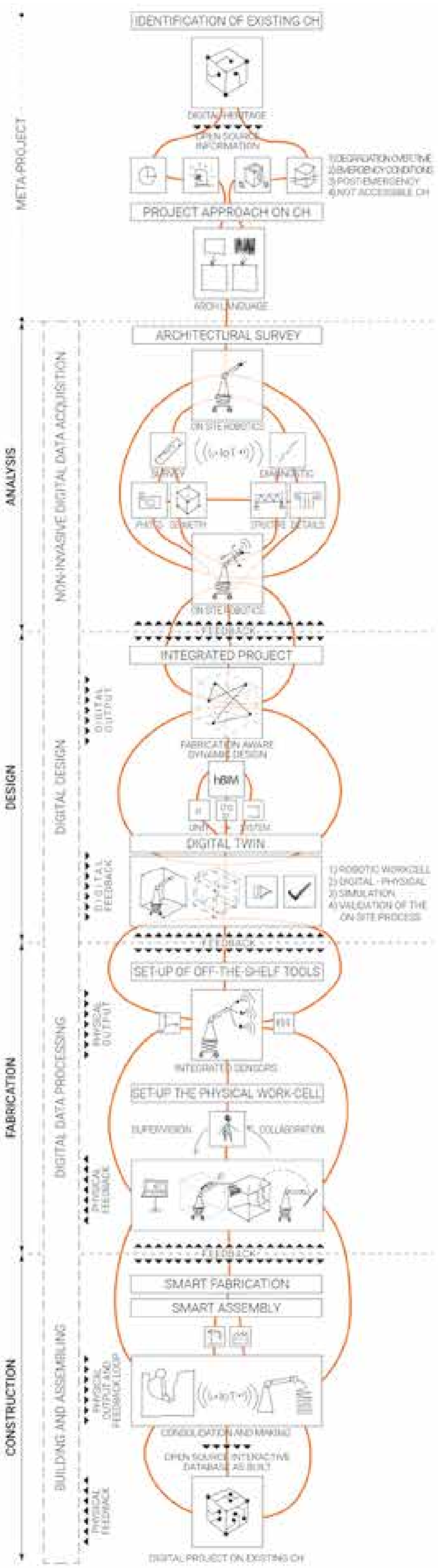
Digital Workflow - HYPOTHESIS



Digital Workflow - LABORATORY EXPERIMENT



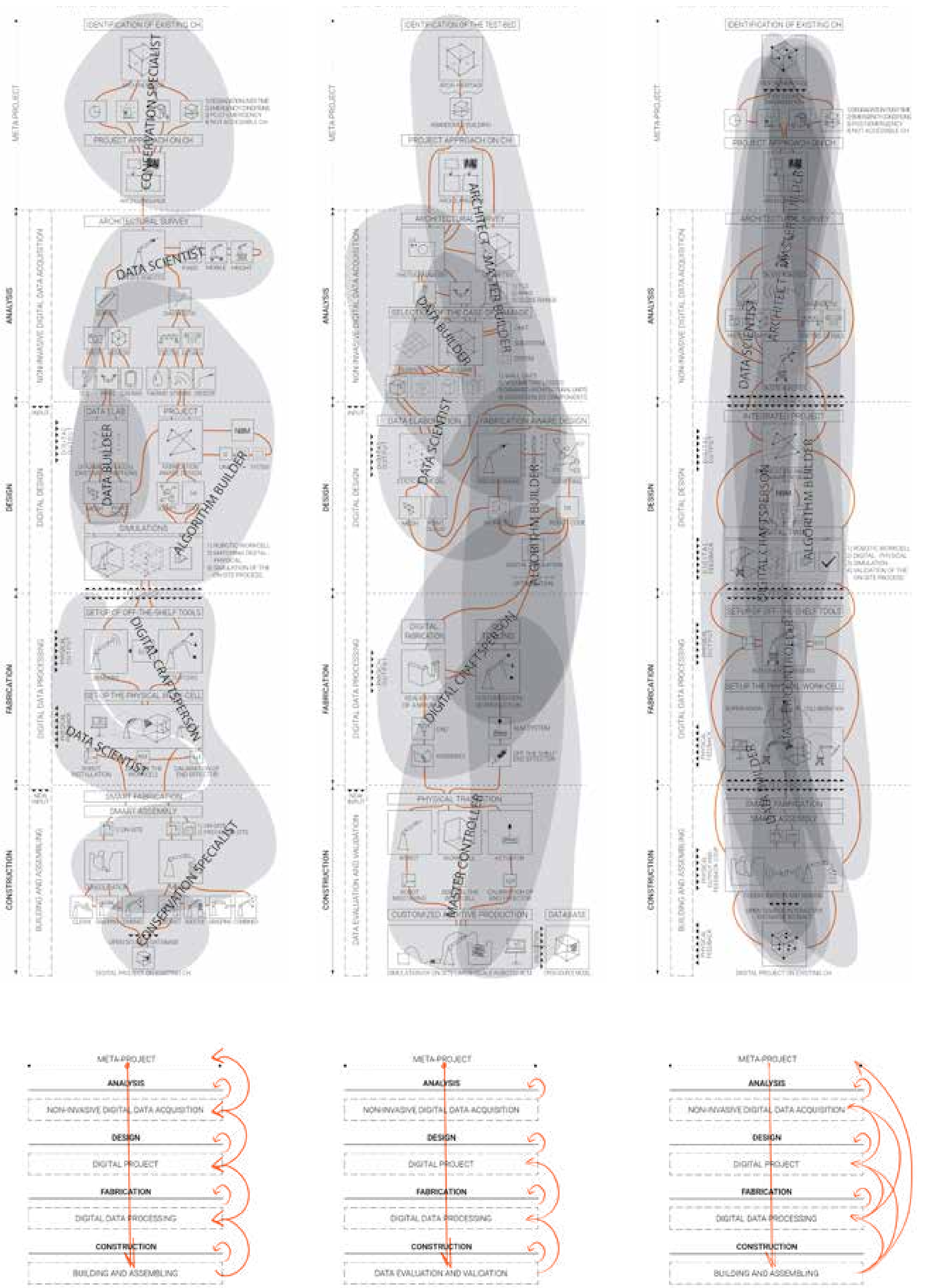
Digital Workflow - FUTURE SCENARIO



Digital Workflow - HYPOTHESIS

Digital Workflow - LAB EXPERIMENT

Digital Workflow - FUTURE SCENARIO



Digital Workflow - HYPOTHESIS

Digital Workflow - LAB EXPERIMENT

Digital Workflow - FUTURE SCENARIO

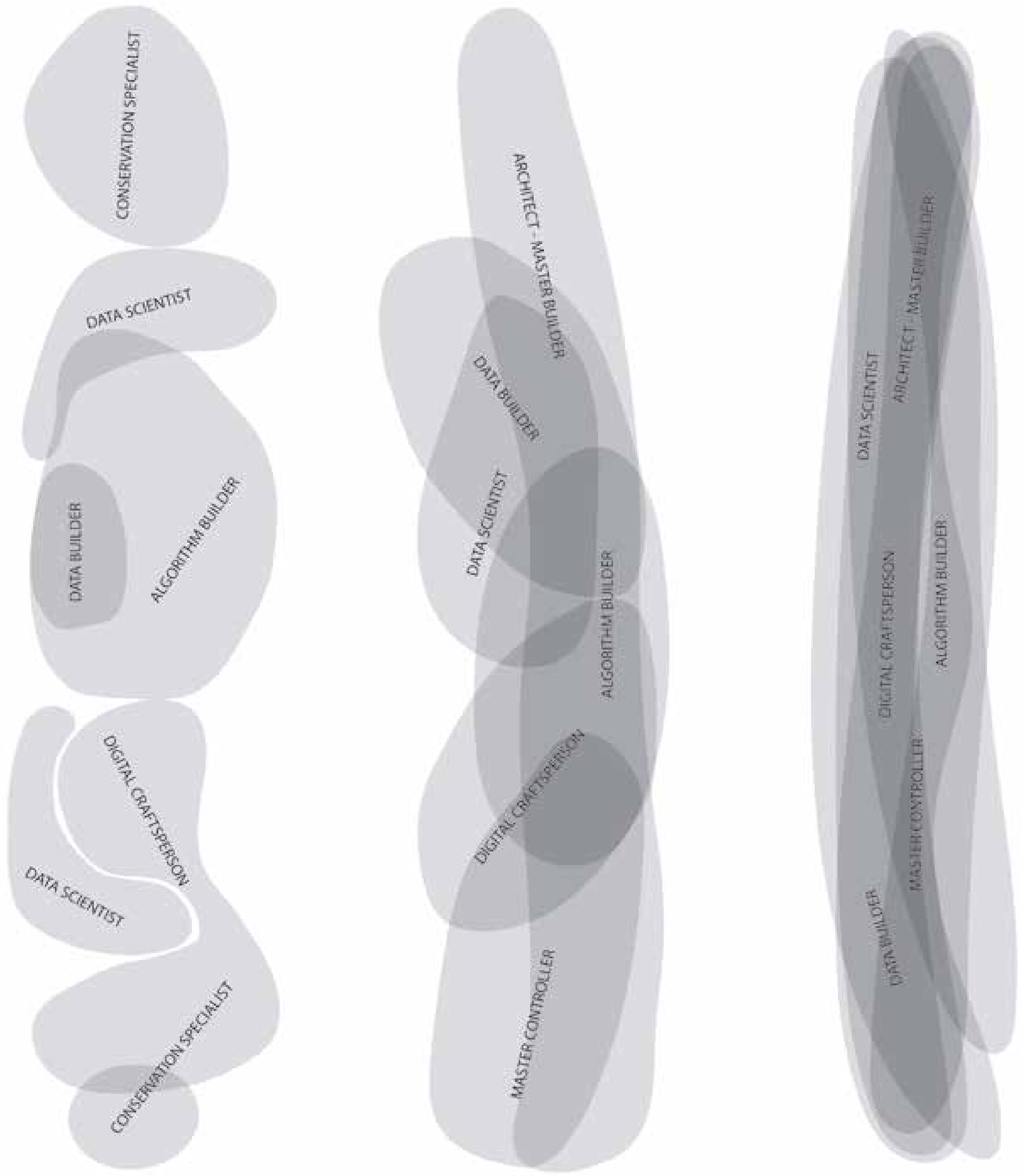


Fig. 9.10 Proposed workflows. They deal with robotic digital fabrication and interventions on Cultural Heritage. Top left: overlapping of the phases of the applied research and the necessary skills to carry out the processes. Down left: operational flexibility and possibility to do iterations during the different phases, from design to construction. In a future scenario, the workflow is more likely to be fluid and open to interoperability. Top right: extrapolation of the skills needed to perform the proposed methodology. The identified skills derive from the technological and digital shift that widespread in architecture since the nineties. From now on, it is necessary to merge data, algorithms, materials science, construction science, and design culture, to make architecture. Cultural Heritage is a premium. It requires special expertise and a master-builder / digital craftsperson approach.

9.2.1 Analysis - first cross section

The analysis phase (Fig. 9.11) conducted during the experiment (WF2), namely the survey of Woodward Avenue presbyterian Church, took place through the use of advanced survey tools based on point cloud collection, data collection in the form of mesh and photogrammetry. In the hypothetical phase it was thought to be able to carry out at least part of these phases using mobile robots on-site,[6] capable of operating both on the floor and in height.

The deepening and increasing pace of technical knowledge has highlighted that today only the most prestigious universities are investing in the technological development of these tools. The robots available on the market are those of an industrial nature, fixed, on tracks, or on rotating platforms. Robots of this type are purchased and then implemented mainly in university or private research centers. The robots are hacked, modified, and customized with sensors that are programmed in an entry level with Arduino or through the programming of ad hoc software. The robot available at LTU is a fixed 6-axis, whose movement on-site was not feasible, which was why the building prototype was reproduced on the basis of the geometric survey and to test the motion-end-effector relationship, before theorizing the use of this tool on the building site.

In the future (WF3), it is expected that the global knowledge on these issues will grow exponentially and that in turn will advance the development of TRL so that AI's integrated robots,[7] and visual and tactile sensors will soon enter the construction market. Together with intelligent robots, the software infrastructure is also expected to be implemented. The software will not only be used to program the robots, but also to display the constructive interventions to be carried out in advance via AR. Together with the design information provided by the technical drawings, with the right equipment on-site, it will be possible to check the toolpaths needed to carry out all the project actions for the customized production of architectural components with real-time updating.

This technical development will allow the dissemination of advanced tools for architects-engineers-designers-makers involved in the construction sector, making them forefront adopters of a sector that historically has always absorbed innovation from other areas.

6 "A Robotic Mobile Platform for Service Tasks in Cultural Heritage", in International Journal of Advanced Robotic Systems: https://journals.sagepub.com/doi/10.5772/60527.
7 "How AI Could Change the Highly-Skilled Job Market", in *Citylab*: https://www.citylab.com/life/2019/11/ai-skill-jobs-work-automation-brookings/602272/.

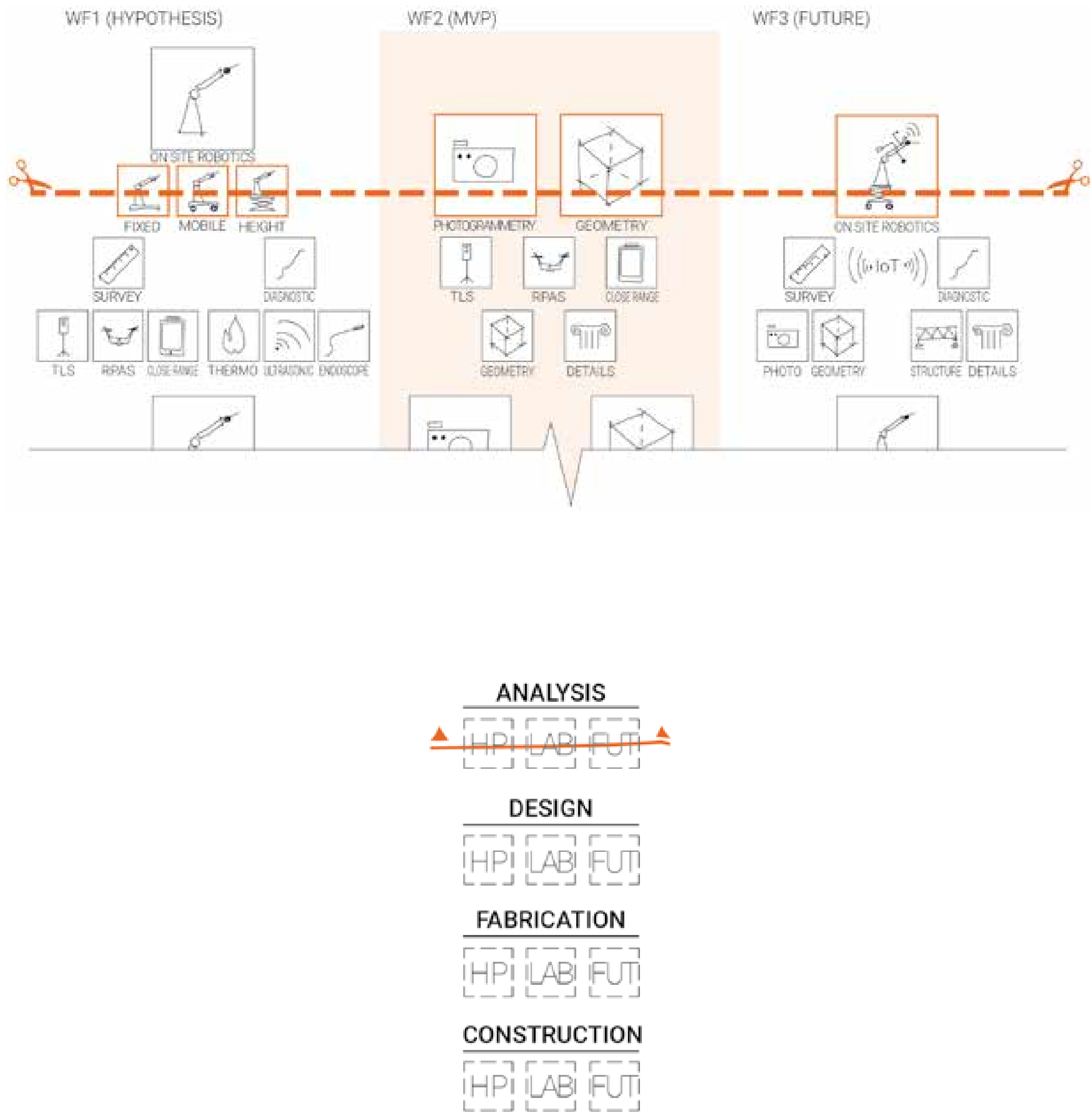


Fig. 9.11 Horizontal section of the workflow. It allows to compare the differences between hypothesis, experiment, and future development within the analysis phase. In particular, this cross-section takes into account the practical approach and tools.

9.2.2 Design - second cross section

BIM, algorithmic, and parametric software are all in various stages of progress and implementation in the digital design phases for architecture (Fig. 9.12). The greatest potential will be offered by simulation tools resulting from the combination of connectivity (IoT) and digital computation. This condition was hypothesized in WF1.

The experiment (WF2) was carried out in the Grasshopper algorithmic design environment with implementation of the Kuka | Prc plug-in. Kuka | Prc is considered an entry-level software suitable for democratizing robotic languages in a teaching environment. Part of this educational tool consists of the simulation of the kinematics of the robot inside the virtual three-dimensional work cell. During the simulation it is possible to view the entire sequence of relative rotations of the axes with respect to the robot's zero.[8] In this stage of analysis the software reports all the lines of code in which there are errors, or singularities. Through this interface it is possible to intervene according to two approaches: (1)intervening directly on the algorithm to modify parameters that are believed to be determinant for errors; or (2) query the software with genetic optimization components (Galapagos fitness function),[9] which automatically finds the error and allows the user to try and correct the error. Through digital iteration "we may or may not intuit some pattern, regularity, or logic inherent or embedded in the structure we are tweaking. By making and breaking (in simulation) a huge number of variations, at some point we shall find one that does not break, and that will be the good one" (Carpo, 2017). With this operational strategy, the designer systematically corrects design errors, avoiding the risk of incurring non-economically sustainable design changes, as expressed in the MacLeamy graph.

In workflow assumptions (WF1), the simulation tool included the robot's work space updated in real-time based on the reconfiguration of new conditions. However this possibility does not exist by default in the software on the market, but it needs a high expertise in computer programming. As expected for hardware, it is imagined that the ubiquity of the IoT will allow robots to be integrated with computer vision capable of providing a large amount of data for digital simulations (digital twin).[10] Each design iteration will include any changes in the boundary conditions, especially in contexts where robots are used on-site and not in standardized environments for prefabrication or on-site prefabrication.

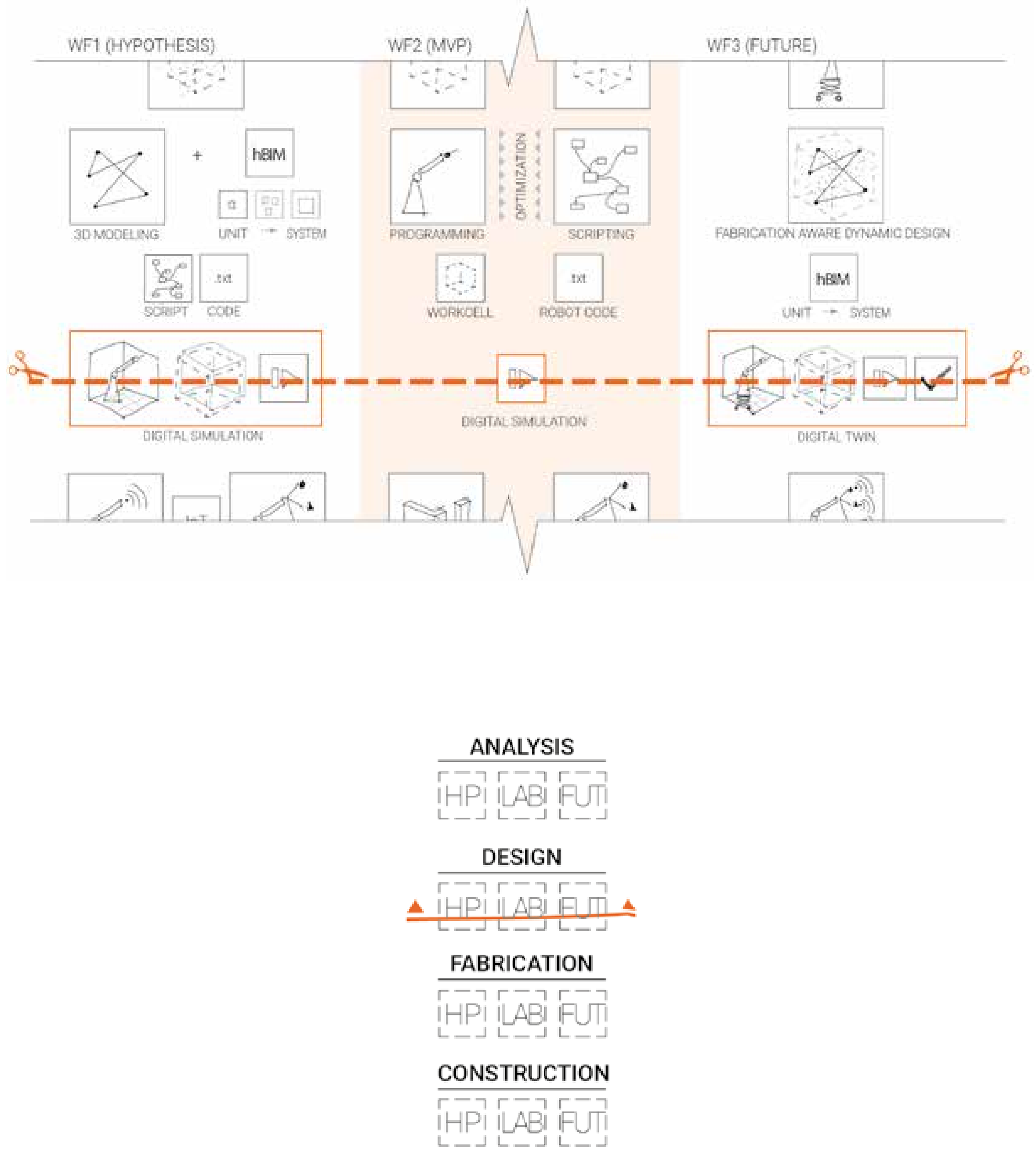


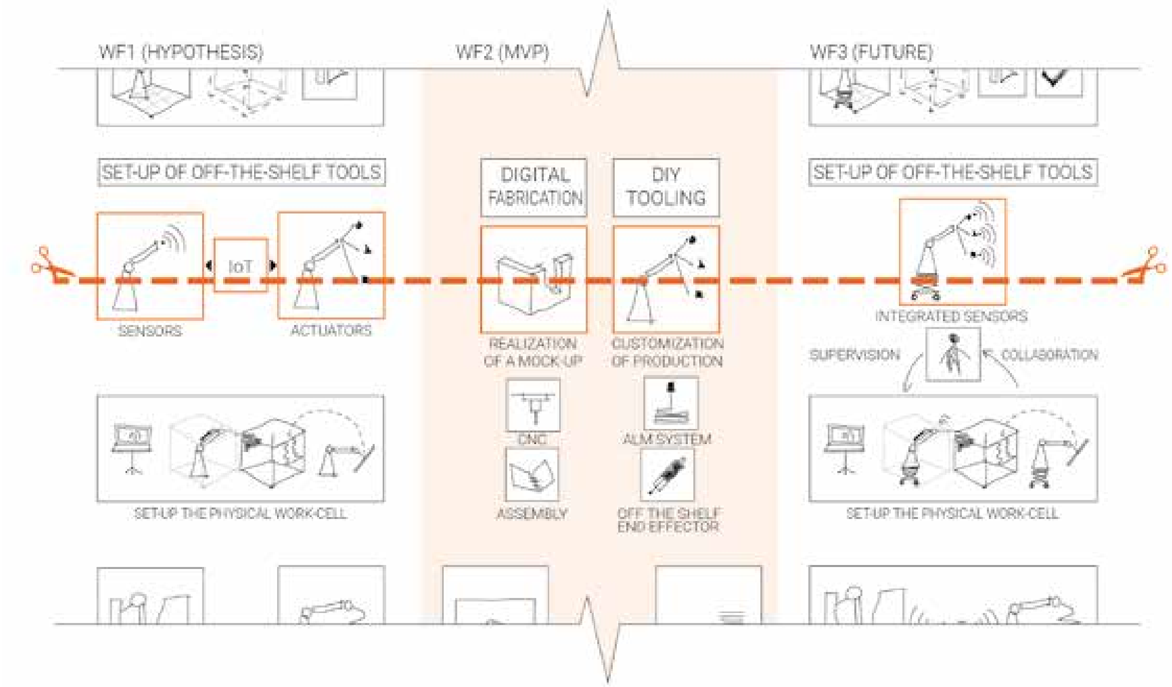
Fig. 9.12 Cross-section of the design phase. The definition of digital twin plays a fundamental role in the future. The ability to quickly connect material and digital data will allow the architecture to enter the digital craft era permanently.

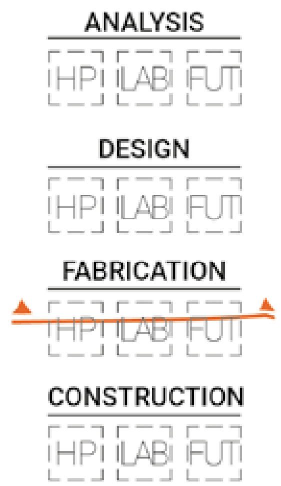
8 Kuka robots set-up instructions: https://robodk.com/doc/en/Robots-KUKA.html.
9 Galapagos evolutionary solver: https://www.grasshopper3d.com/group/galapagos.
10 The digital twin has a specific meaning for building construction. See the white paper " Digital twin definitions for buildings" issued by Sphere - BIM Digital Twin platform. Available at: https://sphere-project.eu/2019/12/26/digital-twin-definitions-for-buildings-white-paper-released/.

9.2.3 Fabrication - third cross section

A fundamental phase of the process is digital fabrication (Fig. 9.13). It is the means for the implementation of the project. The experiment (WF2) was carried out by hacking the robot through a DIY strategy. The robot was transformed into an additive production tool for architectural units in 1:1 scale. The hypothesis (WF1) made in the introduction is valid, or today it is possible to buy end-effectors already on the market and connect them through IoT. The most common extruders generally consist of a container with a motorized piston that pushes the material towards the nozzle.[11] However, this method does not solve the problem of the size of the extruder itself, which is usually installed at the head of the robot. For this research it was necessary to increase the distance between the extruder and the nozzle in order to be able to operate within an irregular context geometry. The end-effector, controlled with Arduino, was created using digital fabrication (desktop 3D printing), based on 3D open source models[12] that were also used to visualize the operation of the system through digital simulation. The inexperience in each of the phases of the research project is considered fundamental to work on projects like this experiment and to make the project easily reproducible, in case of technical errors in the MVP CAD-CAM transition.

In the construction site of the future (WF3) there will be catalogs of robotic end-effectors that can be compared to the tools artisans use for manual processing. Each will have a digital model that will be used in the fabrication-aware design phase. The communication technology will be similar to that used to manage robot fleets[13] like those of Google or Amazon.





11 3D Potter for RAM: https://3dpotter.com/.
12 The open source clay extruder used for the experiment, designed by Bryan Cera: https://www.thingiverse.com/thing:3142561.
13 Formant company. Robot fleet management: https://formant.io/.

Fig. 9.13 Cross-section of the fabrication phase. The experiment was carried out with a DIY strategy. The lowering of the prices of sensors for the development of machine learning and AI will facilitate future building site operations. It will be possible to use off-the-shelf tools. The process will be more integrated and efficient.

9.2.4 Construction - fourth cross section

The last phase to be evaluated is construction (Fig. 9.14). The use of on-site robots formulated at the start (WF1) is a long shot that can become a state of the art before the next decade. The laboratory outcome that was carried out at LTU was achieved through a still fragmented process, which will be strengthened as research progresses. More research will allow us to verify the scalability and efficiency of processes so that industrial robots replace humans in all traditional construction processes that are 4D and 4H. AI integration will play a key role in machine training.

Research projects[14] already exist that provide for the definition of large databases of information divided by macro topics that can be used for machine learning. By loading these data packets into the robot's intelligence, for example, robots will be able to critically recognize the environment that surrounds them (WF3). Imagining that this strategy is applied to architecture, databases can include images and 3D models that allow smart robots to understand the difference, for example, between architectural unit - building - structural or decorative element. This is a further means of preventive control of possible design errors as the machine will be able to understand if the programming instructions received are actually compatible on the elements subject to intervention (diagnostic, consolidation, or construction). There will also be the possibility of using chemical sensors that will allow one to accurately monitor the state of the building, learn faster, and act quickly in the event of natural disasters. Designers and machines will share knowledge and feedback to improve processes.

The development trends of digitalization suggest that in the future there will be less programming and more AI. The AI will be able to provide alternative solutions to incoming data, on which the architect will always remain the supervisor. Connectivity, AI, hardware and software infrastructures will define a new work space shared between designers and robots. In this scenario the design experience will be populated by digital predictive models, which will challenge deterministic culture, anticipating and optimizing intentions. The compression of the experience of AI algorithms, the integration of robots, technical skills to make them work, and the simplified organization of work groups on-site will bring together the pieces of contemporary architectural process fragmentation. In this way every architectural production will no longer be a prototype, an MVP, a "temporary coalition of people and organizations" (Groak, 2002), but the fruit of an intelligent and global design process.

To conclude the analysis, workflow3 is viewed as a methodological draft of how the architect-operator will be able to face the existing construction site using the digital tools available in the Fourth Industrial Revolution. There are the technical and practical aspects that this future professional figure will have to study in order to know how to correctly direct the work, informing the processes with a data-driven strategy, from design to manufacturing. One of the main aspects that remain open for further development concerns the creation of new design methods for which it will be necessary to understand where and how robots can exert the most positively influence. Broad questions have already emerged like which processes should be automated in the future and which should not. Furthermore, it will

14 RobotNet, https://www.robonet.wiki/, and Image-net, http://www.image-net.org/.

be necessary to establish a method to measure the post-construction performance of constructive elements. These objective and quantitative measurements will include the performance parameters that characterize the design process, as well as the benefits regarding material performance, and the construction phase with respect to the impact on energy consumption. Finally, based on the components: cost - analysis - time - expertise - technology - impact, the characteristics of the three workflows analyzed are graphically displayed in the following pages.

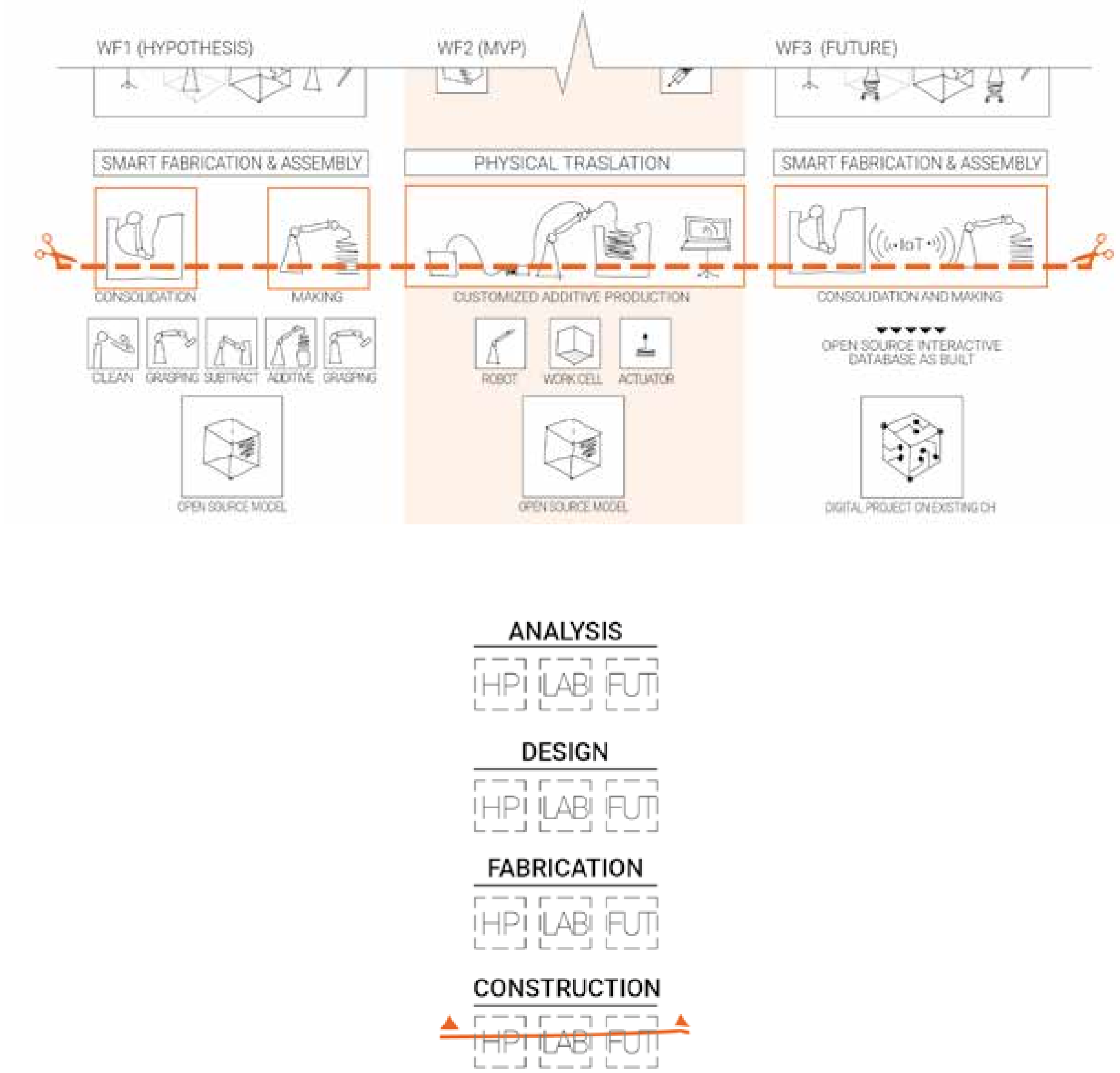
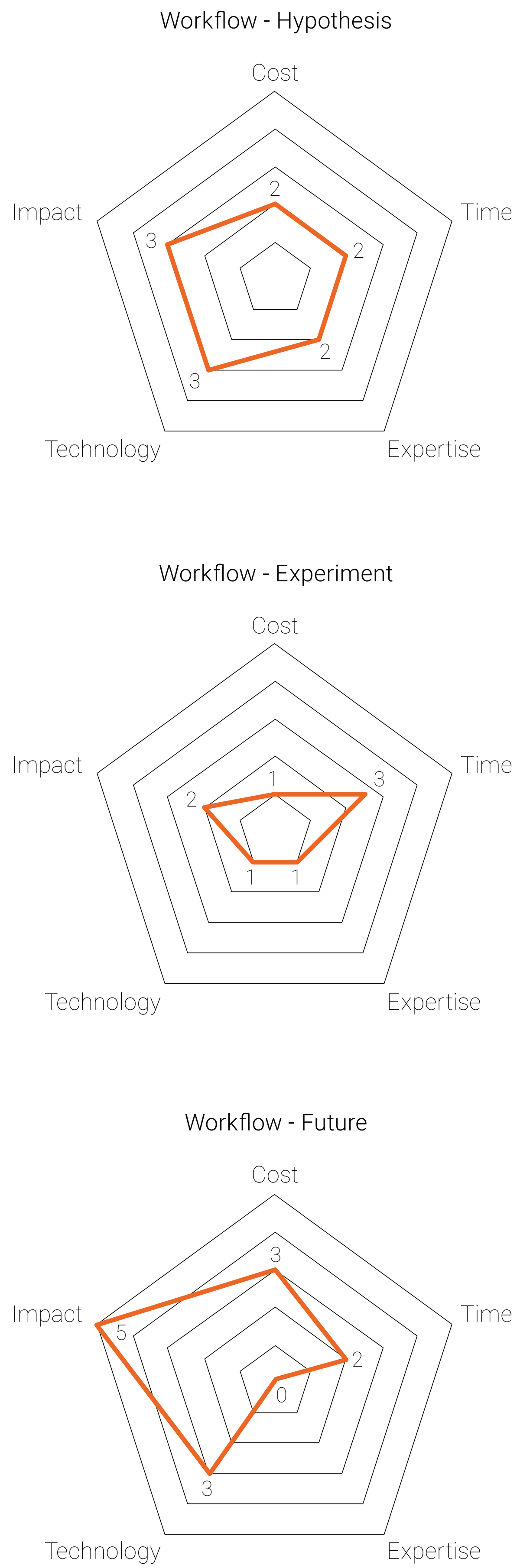


Fig. 9.14 Cross-section of the construction phase. Geometric survey, 3D modeling, digital fabrication, and on-site assembly are the key elements that will innovate the building process as a result of the Fourth Industrial Revolution.



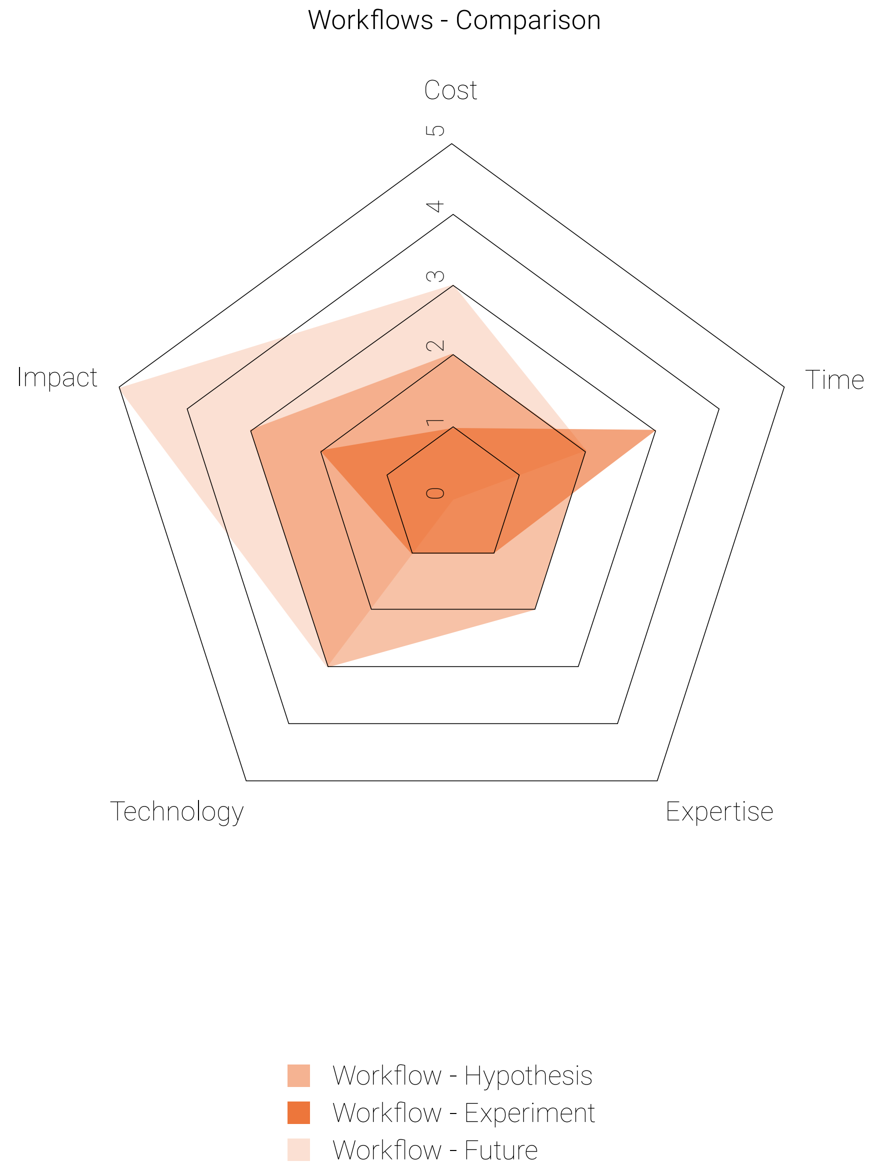


Fig. 9.15 Incidence of the proposed workflow methodology, according to the following criteria: cost, time, technology, expertise, and impact.

9.3 The need of a structured research to address a methodological protocol

The technological advancement of the state of the art in Heritage has defined process and product innovations. To date, product advancements are mainly focused on the use of innovative materials: compatible with traditional structures from a conceptual[15] and technical point of view and performative from a structural point of view. The use of carbon fiber and resin is an example. where the innovation process is especially geared to the overall efficiency of the interventions (Germanà,2011), results from the phases of the typical organization of the site on the constructed (analysis - planning - execution - management) need not be rigidly sequential any longer. The progress of the tools and methodologies for the knowledge of the artefacts and for the diagnosis of degradation have introduced a wide range of digital components in the workflow. Topographic, photogrammetric surveys, 3D laser scanners, and non-invasive instability investigations such as thermographies or ultrasound techniques offer an ecosystem of digital data on which to base and optimize design choices. HBIM's research has also contributed to the enhancement of the phases: survey, design, and management.

Today, process and product innovations contribute to the management and enhancement of Architectural Heritage, from the local to the global scale. Innovations increase the controllability of materials and conservation procedures, to better respond to the needs of sustainability and cultural usability. However, an area remains to be clarified in the near future, namely the practical integration of all disruptive technologies introduced in the market by the Fourth Industrial Revolution. As expressed in the recent research document *Foresight, Hindsight and the Economy* written by Michele Russo and distributed by the AIA (American Institute of Architects) among the challenges that will characterize the architect's profession in the near future there are the "disruptive technologies" that if exploited in their potential can make professional practice more profitable.[16]

If the focus is on the scale of each nation, the need exists for a national research project, dedicated to reliability (Germanà, 2004) of interventions on historical architectural works, capable of achieving lasting results for innovative protection. Smart innovation will continue to translate into future fundamental tools for the definition of a model with both methodological and theoretical protocols. These tools will be defined by experts in the recovery of Architectural Heritage, through which it will be possible to initiate a system capable of the following:

- offsite reconstruction processes, such as customized prefabrication and preassembly of architectural units;

15 As recalled by the lecturer Maria Luisa Germanà in the text "Technological innovation for Architectural Heritage in the dialogue between past, present and future" in *Architecture and innovation for Heritage*, an example among the more discussed in the interventions that foresee physical contiguity between new material and historical testimony is the use of reinforced concrete, "even expressly advocated for ancient buildings in the *Charter of Athens* of 1931 (art.V), widely used for decades even on built archaeological, despite the limited propensity to last and the substantial conceptual, material and technical incompatibility".
16 AIA report: https://www.aia.org/press-releases/25401-architects-expect-more-digital-advisory.

- virtual reality, augmented reality, and real-time rendering, to view, test and validate the design
- autonomous vehicles for road trucks, which has repercussions on the construction stages, on the management and organization of the construction site the same;
- artificial intelligence / machine learning, used to generate universal best practices, and to break free from the relationship between work experience and quality of the result;
- enhanced construction materials, responsive and interconnected construction technologies. microbiology, nanotechnologies;
- drones, 3D scanners, thermal imaging cameras and devices for surveying and diagnostics;
- robotics / industrialized design, to improve productivity in construction;
- additive manufacturing for design models;
- generative and scripting computational tools;
- big data / predictive modeling, to monitor user behavior and predict the progress of the construction process;
- internet of things / sensors to control systems.[17]

This ecosystem of manufacturing tools and digital data defines the Fourth Industrial Revolution. Today the technological advancement is defined by a dialogue between the mentioned tools and it is expected that in the near future a theoretical procedural model will be established that brings together the elements of a new construction system, defined by: robotic hardware, software programming control, and BIM pre and post realization management control. The definition of a protocol could pave the way for the transfer of the theories and the workflow proposed in the architectural practice. The need to pursue this path creates:

- current trends and expected changes in the world of work, towards the progressive cancellation of the 4D (dull, dirty, dangerous, and difficult) and 4H (hot, heavy, hazardous, and humble) professions in favor of a co-botic designer-machine collaboration;
- the now evident potential of robotic systems to reduce production times and costs, the main motivators of innovation in the sector.

International experience in the industrial and research sector has currently established a good knowledge base on these issues. Despite this, there remains a need to investigate the same issues within the complex system that represents architecture, in relation to all the technological systems that make it up and in relation to its certification protocols. Research strategies and industry relationships will be useful if based on a protocol that involves the study of the technical aspects of the design and production process in order to define an on-site workflow 4.0. In the European context, the partnership for robotics in Europe SPARC[18] is pushing the introduction of robots in different market sectors to strengthen an infrastructure that is considered to "save costs, improve

17 Part of this list was prepared by Michele Russo in the document Foresight, HIndsight, and the Economy, for the AIA.
18 "The partnership for robotics in Europe, SPARC is the largest research and innovation program in civilian robotics in the world. It was launched in 2014 by the joint public-private partnership between the European Commission and the robotics industry and academia. Investments under this joint initiative are expected to reach 2.8 billion euros". See: https://ec.europa.eu/programmes/horizon2020/en/h2020-section/robotics.

quality and working conditions, and minimize resources and waste with a tremendous impact on the economy and our society".[19] The leading sectors at present are those of high medical precision, agriculture, and transport. However, a strategic focus towards the construction sector is recognized, with respect to which the main strengths are mentioned: "in the robot platforms for construction sites as well as the automation of existing construction machinery will bring the advantages of automation (reliability, efficiency, safety) to the construction site. Robotic support of human workers and human robots - collaboration / interaction will increase efficiency and make construction in safer, healthier more attractive job. [...] New robot kinematics, platforms and systems will impact the market along the entire value chain. Robotic suppliers will create more robust sensors and actuators. Robotic construction and demolition will also lead to new, robot-oriented design of our built environment" (Robotics, 2016). This transformation must be supported by a solid infrastructure capable of transmitting, connecting, and interpolating data. Architecture is a sector largely influenced by deterministic phenomena expressed in data.

The construction sector has favored the definition of a culture based on the use of data to feed the creative process and increase the quality of the choices made. Quantitative and qualitative data are used as guiding parameters for informed design decisions that are then translated into digital architecture models. In this designer-machine relationship, the computational tool is responsible for structuring and organizing the raw data, while the decision-making aspects remain the responsibility of the data informed architect. Architectural products themselves become databases, which are the result of integrated specialist inputs. In relation to the robotic production on Cultural Heritage, the policy of using open data or closed data will have to be defined and the selection of what is necessary to create information and knowledge to support the design solutions with respect to a specific problem.

A formal protocol is important to formalize the regulation of the use of physical tools and digital tools (digital twin) in the process phases according to a standardized methodology. It can help to structure the work in terms of collaboration of different expertises. The digital twin must enter architectural culture as a project necessity. It should not be considered as an identical copy of reality (process, product, or service), but as a dynamic predictive infrastructure[20] capable of processing data in a fluid and responsive way.[21]

In the construction industry, the simulated digital twin will allow for virtual mapping of such issues focused on the operations on the existing architecture: the workspace object of intervention, possible risks for humans (such as for example in post situations - earthquake), existing building conditions, static behavior, interactions between different materials, and areas in danger of imminent damage.

19 Eu-robotics: https://www.eu-robotics.net/sparc/about/index.html.

20 "What is a digital twin technology and why is it so important", in *Forbes*: https://www.forbes.com/sites/bernardmarr/2017/03/06/what-is-digital-twin-technology-and-why-is-it-so-important.

21 Gartner top 10 technology: https://www.gartner.com /smarterwithgartner/Gartner-top-10-technology-trends-2017/.

The simulation tool has input data for life cycle descriptions, environmental parameters, and maintenance (simulation - management - supervision - maintenance) aspects that are stored in the metaproject phase by BIM and HBIM software. The digital twin can also find space as a product in the market. Once the project team defines the construction parameters by converting the forms into machine paths, it can access a catalog of algorithms associated with different programmable tools. Depending on the size of the robot and the type of end-effector chosen to perform diagnostic, architectural survey, or production operations, the simulations change and the data between one simulation and another is comparable. This could be a further useful element to optimize the process upstream of the design and carry out the most convenient and sustainable workflows (Fig. 9.15).

The physical tools, in this case the robot, are expected to be introduced into the market when the TRL is ready for the jump in application scale. It is expected that the hardware, already in development, will evolve towards lightweight and transportable integrated tools. Within Cultural Heritage, the aim must be to develop precision tools suitable for applications in confined spaces, at all heights, and in inaccessible areas. The formulation of regulatory codes to control the use of autonomous equipment on-site will also be a fundamental step to open an era of innovative construction methods that currently seems unimaginable. Furthermore, in response to the complexity of the contemporary project, the need for a specific regulatory framework for which the operating methods are certified and the project outputs meet certain performance requirements is increasingly pressing. The regulatory codes must also be formulated by virtue of the current need for energy efficiency and optimization of material resources. Resource optimization and the theme of structural performance were arguments used with the First Digital Era to justify the arbitrariness of the form generated by digital processes. Today, however, thanks to refined notions of digital computation, simulation tools, optimization algorithms, and a maturing design field, new design arguments can be considered as guiding elements of information on environmental and technological design processes.

9.4 Timeline of future applications

Today, pilot projects are underway on the use of robotics for new buildings[22] that fit into the complex construction site dynamics. The motivations that lead to this innovative motion are configured as:

- attempt to cut labor costs;
- possibility of extending night shift work by robots;
- ability to perform actions more quickly and accurately.

The main tasks currently under development are those of excavation, assembly of dry elements, painting, and roofing. An example is the European project Hephaestus, which is working on the development of robotic systems (cable-robots with modular end-effectors) for the installation of curtain walls.[23]

22 "The Construction Labor Shortage", in *Forbes*: https://www.forbes.com/sites/columbiabusinessschool/2019/07/31/the-construction-labor-shortage-will-developers-deploy-robotics/.

23 Hephaestus European project: "The proposal addresses novel concepts for introducing Robotics and Autonomous

New construction is a promising research area. National and international statistical projections show how the socio-economic basis for on-site robotic prefabrication will occur in the near future. Industrial robots can be used directly on-site. Contractors will be able to produce technological units to be aggregated on the project site, minimizing the consumption of resources in the production chain and the expenses related to the transport of construction components.

These possibilities encourage experimentation on innovative, non-invasive, and reversible aggregation systems, in favor of open prefabrication, able to provide differentiated answers compared to complex design inputs. However, market indicators hold high attention to the contraction of the current real estate market both on an Italian and European scale. In Italy, the absorption rate of new buildings of 80% in 2007 fell to 35% in 2012 without ever going back to 2019. Investments in the reconstruction sector now reach and exceed those for new buildings. At the same time 70% of the residential real estate stock is composed of buildings originating prior to 1970 and needs to be adjusted to new levels of energy efficiency, seismic safety, inclusivity, and living comfort. On a larger scale, about 35% of the EU's buildings are over 50 years old.[24] 90% of the existing building stock in Europe was built before 1990.[25]

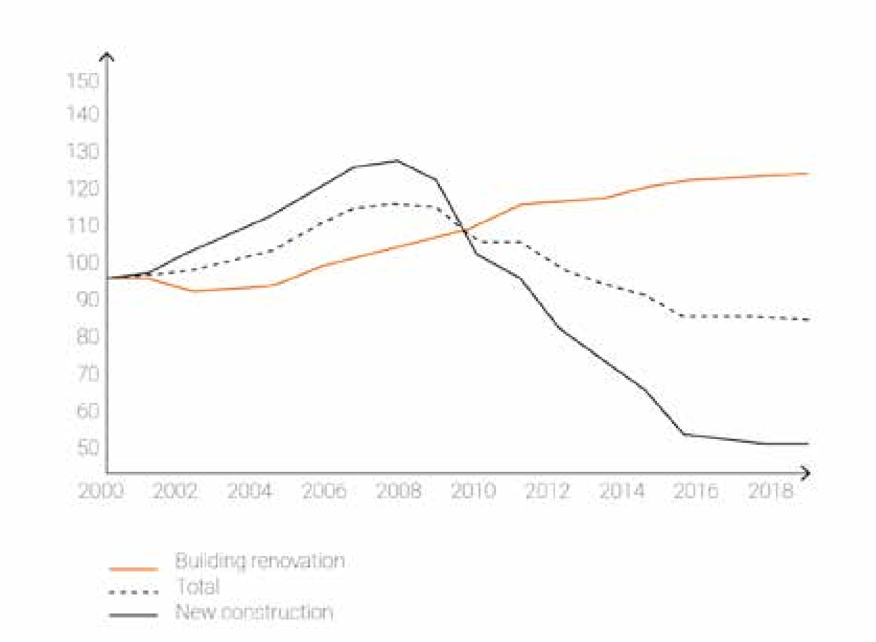
In all likelihood the redevelopment building process will become the area of intervention of most professional activity from now to the next 30 years, (Fig. 9.16, Fig. 9.17) as "buildings built today will only represent 10-25% of the building stock in 2050"[26] (Commission, 2018). It will require the definition of information tools to support complex decision-making processes, able to integrate different skills, at different scales and at different times in the life cycle of buildings. These data lay the foundations for a territory of research and experimentation in which robots can interface with constructed buildings, learning from the geometric - technical - organizational - design - process complexities inherent, while exploring the first application possibilities for Architectural Heritage. Surely predictive models will help to marginalize design errors. At the same time, it seems that the circumstances are optimal to be able to carry out tests on minor architecture, before making the experience on the conservation of cultural assets more robust.

Systems in the Construction Sector where, at this moment, the presence is minor. Specifically, the Hephaestus project focuses on highly risked and critical construction tasks such as prefab wall installation". See: https://cordis.europa.eu/project/rcn/206251/factsheet/en.

24 "It has been estimated that up to 97% (ie all buildings built before 2010) needs partial or deep renovation to comply with the long-term strategy ambition. Taking advantage of technological progress (eg ICT and smart building technologies) should aim at increasing the depth of renovation. Measures should be targeted towards the worst performing segments of national building stocks, including demolition and replacement by new buildings". See: https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf.

25 A European long-term strategic vision for a prosperous, modern, competitive, and climate neutral economy, study for the ITRE Committee: http://www.europarl.europa.eu/RegData/etudes/STUD/2016/587326/IPOL_STU(2016)587326_EN.pdf.

26 State of the building stock briefing, in *Building Performance Institute Europe*: http://bpie.eu/wp-content/uploads/2017/12/State-of-the-building-stock-briefing_Dic6.pdf.



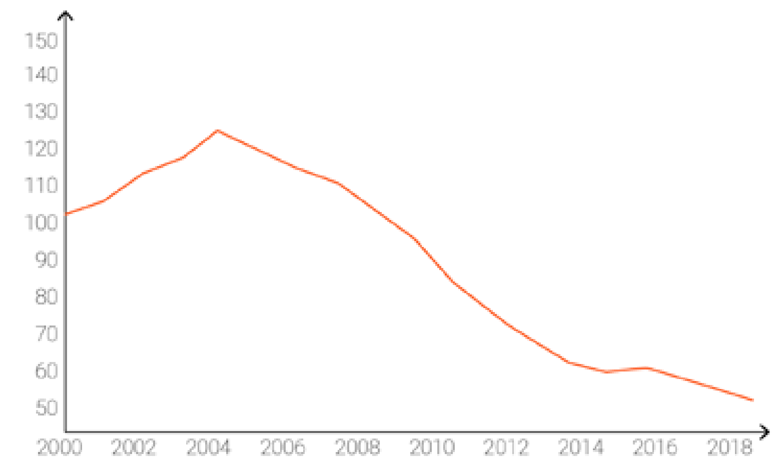


Fig. 9.16 Investments in residential constructions (index: 2000 = 100), in Italy. Source: ANCE, Associazione Nazionale Costruttori Edili, Osservatorio congiunturale sull'industria delle costruzioni, January 2019, p.10.
Fig. 9.17 Investments in non-residential public buildings. Source: ANCE, Associazione Nazionale Costruttori Edili, Osservatorio congiunturale sull'industria delle costruzioni, January 2019, p.13. In the last decade, Italy has shown a significant trend in the construction industry. The building crisis that started in 2007 and the aging of buildings, and the slowdown in the national economy made it necessary to invest heavily in the renovation of existing building stock. In Europe, the amount of buildings that will necessarily be subject to renovation in the coming years opens the way to innovation. In this sector, robotics and automation can provide answers in terms of process efficiency and economic management.

It will be advantageous to test robotics in architectural-executive practice on existing buildings[27] for refurbishment, deep renovation,[28] and retrofit operations.[29] These are all elements that set the optimal conditions for a disruptive change in the construction sector and for the development of innovative solutions.

An example involving Italian companies in the European research scenario is the P2-endure project. It promotes "evidence-based innovative solutions for deep renovation based on prefabricated Plug-and-Play systems in combination with on-site robotic 3D-printing and Building Information Modeling (BIM)",[30] opening new scenarios in the field of redevelopment and retrofitting. Experimentation of the tools and technologies developed is still ongoing.

From new construction, to the deep renovation, to the Heritage: when these scenarios of the Fourth Industrial Revolution enter a single integrated digital infrastructure, the construction industry will finally become part of the Digital Transformation ecosystem.

9.5 Education and new professions

"The illiterate of the 21st century will not be those who cannot read and write, but those who cannot learn, unlearn, and relearn" [Alvin Toffler, 1984]

In the future design and construction scenario that lies ahead, the master-builder designer will take care of the entire production chain. This professional will need to be able to summarize the complexity of Industry 4.0, Work 4.0, and lead flexible construction 4.0 workflows with respect to the logic that governs the agreed upon manufacturing processes. Experiments that investigate issues related to computation and digital fabrication as elements capable of triggering innovation processes testify to an area of study increasingly oriented towards architectural-executive practice that involve industrial processes and academic training.

The study of robotic state of the art in architecture has allowed for an understanding of how academic research is increasingly approaching the construction, material science, and new technologies to favor the transition to on-site prototyping of building elements. New technologies in architectural design practice will consolidate this relationship making it possible to collect

27 The Commission calls for a climate neutral Europe by 2050: https://ec.europa.eu/commission/presscorner/detail/en/IP_18_6543.
28 The Energy Efficiency Directive of the EC (2012/27) defines, with the term Deep Renovation, the building restructuring interventions, economically advantageous, which allow to reduce the energy consumption of a building by a value equal to at least 60 % compared to the condition prior to the intervention. See: https://cordis.europa.eu/article/id/401127-deep-renovation-new-approaches-to-transform-the-renovation-market.
29 Retrofit in Europe: https://ec.europa.eu/jrc/en/publication/towards-nearly-zero-energy-buildings-europe-focus-retrofit-non-residential-buildings.
30 P2Endure project: https://www.p2endure-project.eu/en.

the economic resources necessary for carrying out of scientific research activities and the training of master-builders able to interpret future design requirements. Most of the case study experiments analyzed took place in a laboratory environment. In order for a transition from a prototype workflow to a real construction 4.0 workflow to occur, it will be necessary for research centers to focus on solving concrete problems in the construction sector. Process and product innovations, from design to construction, and the results of research that will be able to advance the various technological TRLs will be fundamental to encourage investment and accelerate technology transfer from the academy to professional practice.

In the article "8 Things Every School Must Do for the Fourth Industrial Revolution"[31] published in Forbes in May 2019, the need is expressed to strengthen the role of education for the next digital professionals, who will have to have the skills to manage smart technologies like AI, AR / VR, big data, automation, and IoT. Among the key aspects that are mentioned, there is a need to:

- support students to develop the skills and mindset to do anything in their future rather than a particular "something";[32]
- improve STEM education (science, tech, engineering, math) as there's no doubt every worker in the future will need some technical skills;
- develop human inherent abilities like creative endeavors, imagination, critical thinking, social interaction, and physical dexterity so they are equipped with partners in the future rather than competing with them;
- prepare lifelong learners because in the future people start a career path and only grow with one role;
- prepare students to perform jobs that today don't exist;[33]
- personalize teaching by bringing technologies such as AI and machine learning;
- practice curiosity, problem-solving skills, inquisitiveness and the iterations of failure; schools need to provide learning environments that will enable users to be creative using a variety of physical and digital tools;
- train students to have a global mindset and look at international demand and languages of emerging markets;
- make changes to post secondary education[34] forging stronger ties between institutions of higher learning and industry; it is essential that the seeds of learning are set up in schools by offering them the opportunity to learn topics beyond their core curriculum and develop a love for learning.

31 1. Redefine the purpose of education 2. Improve STEM education 3. Develop human potential 4. Adapt to lifelong learning models 5. Alter educator training 6. Make schools makerspaces 7. International mindfulness 8. Change higher education. See: https://www.linkedin.com/pulse/8-things-every-school-must-do-prepare-4th-industrial-revolution-marr/.
32 "The future of jobs report", in *Weforum*: https://www.weforum.org/reports/the-future-of-jobs-report-2018.
33 According to a Dell Technologies and Institute for the Future (IFTF) report, 85 percent of the jobs in 2030 don't exist yet. See: https://www.delltechnologies.com/content/dam/delltechnologies/assets/perspectives/2030/pdf/SR1940_IFTFforDellTechnologies_Human-Machine_070517_readerhigh-res.pdf.
34 "How students can graduate can graduate qualified for Fourth Industrial Revolution", in *Weforum*: https://www.weforum.org/agenda/2019/01/how-students-can-graduate-qualified-for-fourth-industrial-revolution/.

This research advocates the importance of the study from an educational perspective. In the near future, designers will need new skills and new approaches to architectural practice. More people are needed in this discussion. Higher education has an impactful role in preparing future professionals. Teaching in preparation for the Fourth Industrial Revolution will mean educating designers who will have a fundamental role in projects as master-builders. Process information will also establish a link between actors and project phases that are commonly distinguished as designers, construction industry, owners and occupants (Deutsch, 2015), which will operate as data enabled project teams.

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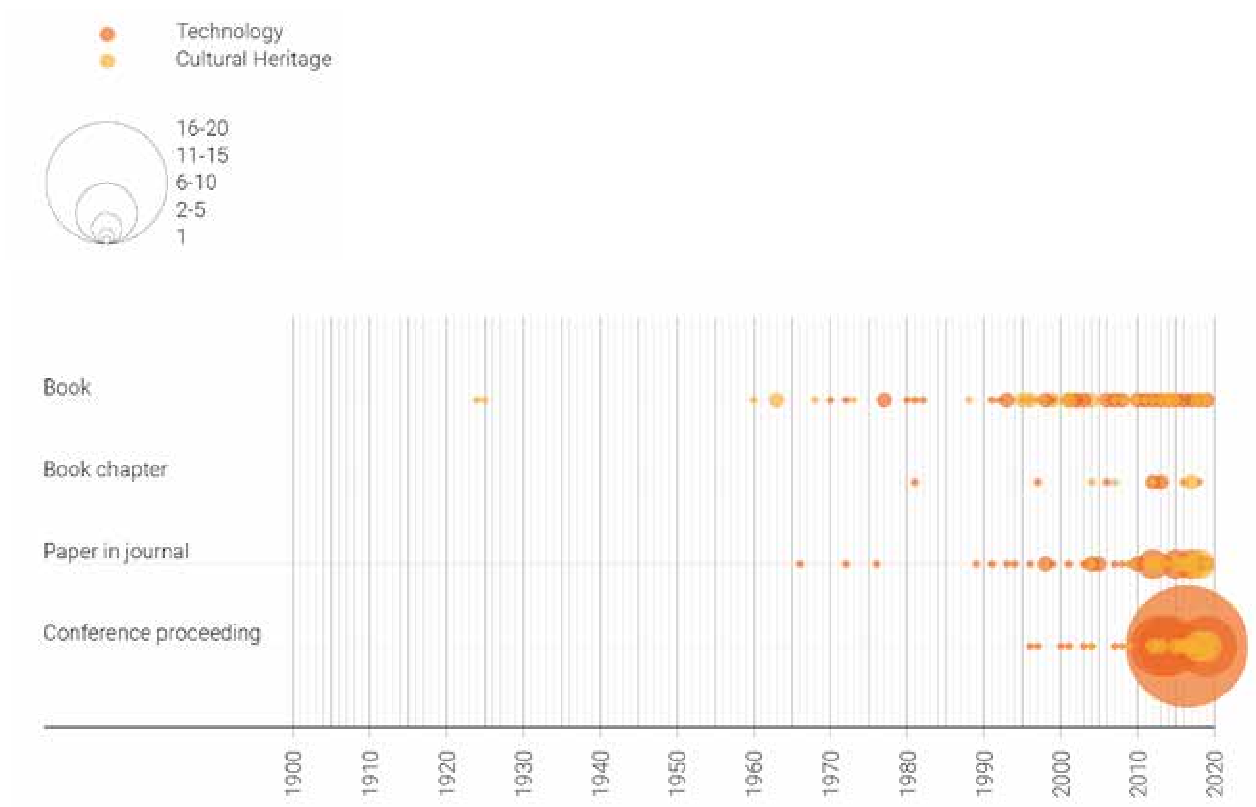

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IG account

3D Potter: @3dpotter

ABB Robotics: @abbrobotics

ACADIA: @acadiaorg

Accenture Technology: @accenturetechnology

ANYbotics: @anybotics

Architectural Association School of Architecture: @aaschool

Atonaton: @atonaton

Ballard International: @ballardinternational

Bartlett B-Pro: @bartlett_b_pro

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CMU School of Architecture: @cmusoa

College of Architecture and Design at Lawrence Technological University: @ltu_coad

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Smart Geometry: @smartgeometry
Taubman College: @taubmancollege
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