The Evolution of 3D Printing in AEC: From Experimental to Consolidated Techniques

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Additional information is available at the end of the chapter

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Abstract

The chapter leads the reader through the historical development of additive manufacturing (AM) techniques until the most recent developments. A tentative taxonomy is added to the historical perspective, in order to better understand the main lines of development and the potential cross-fertilization opportunities. Some case studies are analyzed in order to provide a clearer picture of the practical applications of AM in architecture engineering and construction (AEC), with a particular attention to the use of AM for final products rather than just prototypes. Eventually, some thoughts are shared as to the impact of AM on AEC beyond the mere cost-effectiveness and well into the potential change of paradigms in how architecture can be thought of and further developed embracing the new world of opportunities brought by AM.

Keywords: experimental technologies, innovation in AEC, mass customization, 3D-printing, additive manufacturing, digital fabrication

1. Introduction

3D printing can be nowadays considered a consolidated technology, at least in its technical aspects. However, the adoption of such manufacturing technique to architecture engineering and construction (AEC) is not widespread yet, as the sector is not yet completely ready for the introduction of innovative production methods, in comparison to other more innovative sectors. Some experimental case studies have been developed looking at possible applications of 3D printing in architecture and construction, but the gap to close is now related to a consolidated way of employing innovative manufacturing techniques.

2. Production techniques in AEC

The historical evolution of architecture is closely linked to that of construction techniques. The combination of available techniques and workforce—in quantity and quality—has driven the sector since antiquity, and architects had to know and carefully consider them as a premise of their design. Moreover, while some techniques have emerged from within the field of architecture, in the effort of solving construction problems, very often it was the spillover of advancements in other fields of science and technology that determined the adoption of new production techniques in architecture.

While such combination of workforce skills and production techniques has been consistent throughout the centuries, there have been some radical paradigm changes in their combination. In particular, while a sort of batch production of some architectural elements was present since antiquity, as well as in gothic architecture—as for bricks, tiles, and column drums—starting with the industrial revolution, such production in series acquired a more industrial character, and the relevance of skilled labor started to decline, while mechanized processes took off as the most decisive factor in production costs and quality. Modularity, which previously was rather an ideal set of geometrical relationships and proportions related to orders, started to become a necessary way of streamlining the production in series of identical base components, the only way industrialization could lower production costs as well as assembly times and efforts. Architectural practices and theories had to reflect these needs, and especially with the Modern movement, the trend toward simplification and use of standardized elements became common practice. The case of 'The Eames House, Case Study House 8' by Charles and Ray is a paradigmatic example thereof: the building was even designed and assembled starting from 'off-the-shelf' standard pieces, while trying to create an individual architectural character. Production in this case was a given before the design, and not the result thereof. Fast forwarding in history, the use of building information modeling (BIM) software has connected this trend to the realm of the design in the virtual (software) environment, especially as it allows and even encourages the use of available and industrially pre-fabricated architectural elements, such as doors and windows, and also rebars, trusses, and the like.

On the other hand, starting from the 1960s, the degree of geometric freedom and control over the produced elements started to increase through the use of computer-aided design (CAD) and computer-aided manufacturing (CAM) software, even though the constraints of a required standardization of elements continued to be present for a cost-effective production. Through Bézier curves and Non-Uniform Rational B-Spline (NURBS) modelers, it was now possible to create more organic and complex shapes. An early example thereof was the Renault 'Unisurf' software used to design and produce car parts. However, the process often required non–computer-controlled phases and the mass-production of standardized pieces.

It was in the last 10–20 years that a more streamlined and integrated use of computer numerical controlled (CNC) machines started to allow for a new change in paradigm within the architectural field. While a few centuries ago, the spillover of industrialization techniques meant that standardization and simplification had to become the design approach to architectural projects because industrial production required identical elements to be mass-produced in order to lower the cost per unit, now it became possible to cost-effectively mass-produce elements that are different from one another, i.e., customized elements. It is the 'mass-customization' paradigm. The use of CAD/CAM software became the key tool in the hands of designers and architects to harvest this new production potential. In fact, the 'virtual' design within the software could be now transformed into something tangible driving the production machines directly from the computer and without the need for any 'translator' or skilled human intermediary. As in the First Industrial Revolution, workforce manual skills were not relevant anymore, but unlike under the previous paradigm, it was now not necessary or advantageous to reduce the complexity of the design elements and to embrace radical simplification. As we will see dealing with 3D printing techniques, it is worth noticing that this new approach started off as a convenient tool for fast prototyping, but due to technical advancements, it is potentially becoming a method for the production of final parts or even entire architectures, as it has already become a production technique in some fields of advanced engineering, such as aeronautics.

3. 3D printing history related to construction methods

Additive manufacturing (AM) is possibly the most disruptive production paradigm stemming from the adoption of CNC machines. It promises to transform a(ny) virtual shape designed in a software environment to a real-world object, as much as 2D printing is transforming virtual pixels into ink dots on a sheet. It requires that the object to be printed be 'rasterized' into discrete elements, which usually is performed through the use of Mesh geometries in the CAD environment. More often than not, additive manufacturing techniques are actually working by layered 'slices' (sections) of the desired object, so that the final shape results from the combination of subsequent, 2D designed, layers of material with a standard thickness.

3.1. History and evolution

1980–1981: Hideo Kodama (Nagoya Municipal Industrial Research Institute) invented and described two first additive manufacturing techniques based on photo-hardening of plastic polymers. This seminal work can be considered the ancestor of both photopolymerization and stereolithography. An application for patent was filed, but the inventor did not follow up within the required one-year deadline after application [1, 2].

1984: Jean-Claude André (CNRS), Alain le Méhauté (CGE/Alcatel) and Olivier de Witte (Cilas) filed an application for patent of stereolithography, i.e., an additive manufacturing method whereby a laser beam selectively hardens a UV-sensitive liquid resin, following a sequence of cross-sections of the object to be printed. The patent filing was abandoned, and Chuck Hull filed a patent, granted in 1986. The system was based on ultraviolet laser light beams hardening cross-section by cross-section a resin contained in a vat. The .stl file extension Hull adopted is still in use today for most AM. He also founded 3D Systems, a company manufacturing 3D printers.

1987: Carl R. Deckard invented at UT-Austin the selective laser sintering technique, based on high-power (usually pulsed) laser beam that selectively fuses powder particles along cross-sections of the desired shape. The powder can consist in plastic, metal, ceramic or glass, and is usually pre-heated in the bed just below the fusion point. A patent for a similar technique was filed in 1979 by R. F. Housholder, but it was not commercialized.

1989–1990: S. Scott Crump invented and patented the most popular 3D printing technique to date, especially for hobbyists and low-budget labs: fused deposition modeling (FDM). It consists in the deposition of fused material—most commonly plastic—layer by layer, according to a .stl file. The first machines were commercialized by Scott Crump's company Stratasys starting from 1992, and a patent was granted (expired in 2009).

1993: MIT developed what, strictly speaking, was considered 3D printing. The technique consisted in the binding—layer by layer—of a bed of powder using an inkjet printer, hence the name. In 1993, yet another technique was introduced by Sanders Prototype, Inc., now Solidscape: the 'dot-on-dot' technique. It was based on polymer jetting with soluble supports, yielding very high-precision results. The models were originally printed in wax.

1995: The Fraunhofer Institute ILT, Aachen, invented the selective laser melting process. The process—which yields precise and mechanically strong outputs, given the use of metal alloys, and can handle nested and intricate geometries—consists in the melting, layer by layer, of metal powder by means of a laser beam. Selective laser sintering is a similar process, whereby metal powder is not completely fused, hence does not form as much of a coherent and homogeneous mass as an output.

1999: Bioprinting techniques were successfully experimented at Wake Forest Institute for Regenerative Medicine.

2004: Adrian Bowyer developed the RepRap open-source project, aimed at creating self-replicable 3D printers, in an effort to diffuse and democratize AM technology.

2008: Shapeways was launched in the Netherlands. It consists in an on-line service, allowing users to send 3D files to have objects printed and sent to the required address. The service uses various techniques and materials, which today include several precious metals.

2009: Makerbot created a DIY kit for 3D printers which will highly contribute to the diffusion of the technique in many households.

2011: The opportunities offered by 3D printing techniques as production rather than pure prototyping tools were made even clearer by the Southampton University Laser Sintered Aircraft (SULSA), an unmanned aircraft whose structure was printed, from the wings to the integral control surfaces by a laser sintering machine, with a resolution of 100 micrometers per layer. The unmanned aerial vehicle (UAV) could be assembled without tools, using 'snap fit' techniques.

2014: Airbus Operation GmbH filed a patent for 3D printing an entire airplane structure. The technique is interesting also due to the 4D-printing-like features: a study on materials deformation, especially with respect to each other, is used to further strengthen the structure, by exploiting the resulting forces.

Overall, while the seminal ideas of the main additive manufacturing techniques dates back to the 1980s, further development and combination among techniques have gradually implied a shift in the potential use. In fact, while AM started as a means to rapid prototyping objects, especially for engineering—where the limited availability of materials and the lack of mechanical strength was not an issue—it now starts being adopted as a whole new way of producing final elements, given the improved quality of the output and the materials that can be used. Such opportunities could potentially disrupt the entire industrial processes and supply chain, enabling diffused fabrication facilities to such an extent that a so-called '0 Km factory' paradigm could emerge. 'Called microfactories, these diminutive factories drastically change how we produce large consumer goods for unique local needs' [3].

Finally, it is worth noting that, having these techniques not reached the full maturity phase yet, it would be pointless to analyze all the alternative methods and machines which have been invented and adopted for the most diverse projects. It seems therefore more useful analyzing the main categories, trying to provide a taxonomy thereof, bearing in mind that research is currently blossoming in the field, often hybridizing techniques to reach specific goals.

3.2. Taxonomy (and best sorting criteria): a material-state-driven categorization

Devising the 'most appropriate' classification criteria for additive manufacturing is not an easy task. Different approaches have in fact been taken into account in literature for classifying additive manufacturing processes. 'In particular Karunakaran exposes different possible options. A first option is to take as the driving aspect the type of material printed by the machines, which can turn out to be problematic because some machines can print more than one material typology. A second option refers to the material matrix, thus the ability of printers to work with a monolithic, composite, or gradient matrix, in terms of materic composition and properties, but it may result too specific with respect to the scope of the research. Another possible classification is according the final application of printed objects, which ranges from the visualization model to the high-end engineering part; again here, some printers may be used for different purposes, and moreover this subdivision would not clarify the different classes of layer manufacturing technologies and their behaviours. Always according to Karunakaran, more subdivision options can be referring to number of materials involved, on the energy source (laser, EB or arc) used, on the Boolean nature of the manufacture (laminated, powder-bed or deposition) or differencing methods of joining particles, but these approaches are too generic or too specific, not allowing a proper classification of the processes. The approach used by Gibson, is to manage the additive manufacturing techniques according to the starting condition of the material before it is worked by the machines. He defines liquid polymers, discrete particle, molten material and solid sheet systems. Often machines can print different classes of materials, and for different final purposes, but each printer can handle just materials in specific initial states, therefore this criteria is defining a proper subdivision which highlights the characteristics of the material processing, defining advantages and disadvantages of every process category' ([4], pp. 38–39).

We decided to adopt as sorting criteria two main aspects, which are *de facto* combined within the current digital fabrication techniques: 'state' of material, and additive process. In fact, groups of machines will tend to differ based on the state the materials come—here, we refer to grains, filaments, and liquid as 'states'—much more than they differ based on the kind of material. Many machines will be able to use different kinds of plastics and even metals, but require them to be in one specific state. As to the process, it tends to correlate strictly with the material state: for instance, any sintering technique requires a bed of grainy material, as it acts through the bonding of some grains as a way to create the final shape. Grains are a geometrical pre-requisite thereof. Similarly, stereolithography requires liquid resins to be shaped and hardened through light, which again requires a specific material state as a starting point.

Based on the chosen sorting criteria, the main available additive manufacturing techniques can be summarized as follows.

3.2.1. Extrusion of fused/liquid material

These techniques share the common feature of a 'printing head' consisting in a moving nozzle that deposits layer upon layer of material.

3.2.1.1. Semisolid material extrusion

There are two main machine types: Gantry (or Cartesian) and Delta (**Figure 1**). Gantry is based on an extruder moving along the Cartesian X- and Y axes, while the plate is moving along the Z axis layer by layer. Delta systems, on the contrary, are based on three arms connected to universal joints at the base, which move within parallelograms, maintaining a lightweight end-effector in the right orientation. It yields faster and more accurate output, also given the lightweight traveling parts. While plastics are the main material used with this technique—specifically thermoplastics, especially ABS and PLA, and also nylon, PET, HIPS and TPU—ceramics, clay and cement were recently experimented with.

As to the output, some aspects are noteworthy. First, the printed material tends to show anisotropic properties, and the strength in the z direction is usually much lower than in the x and y direction. Second, the printed objects show 'stepping', i.e., a nonsmooth, layered surface based on the slicing layers adopted for printing. Third, not any kind of geometrical shape can be produced with this technique: in fact, a maximum 45° of overhang, slanted parts can be produced without the creation of extra supports, which need to be later removed. Lastly, speed is a serious limitation for this technique to be used outside the boundaries of mere prototypation: a cube of 20 × 20 20 cm may require more than 24 h to be printed.

Other two less common machine types are the polar and the robotic arms. Polar machines work based on an angle and a length, and need only two motors, while the Gantry needs three. The robotic arm is not just a printing machine per se, but a printing head can be attached to a robotic arm. Potentially, it delivers much greater flexibility and printing dimension, especially if the arm is not fixed on the ground. Both techniques are quite experimental and not very widespread.

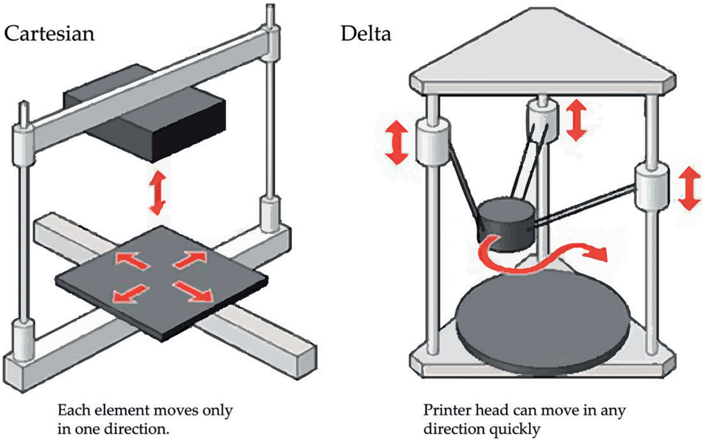

Figure 1. Main systems of deposition techniques (https://tinyurl.com/yayr8ze5).

3.2.1.2. Semiliquid material extrusion

While not a consolidated technique, it has been experimented with by artists and researchers. It consists in the extension of the previously analyzed technique to the use of clay and similarly 'wet' materials. The main difference—though the process tends to vary for each experiment—is the absence of a heated print head, since the material does not have to be fused, while some kind of pressurized mechanism is usually present to force the muddy material through the nozzle.

The possibility of using typical construction materials in architecture—such as clay and concrete—makes this technique promising for architectural projects. However, for the time being the quality of the outcomes in terms of 'resolution', precision and printable geometries is not yet sufficient for real projects outside the field of research.

3.2.1.3. Contour crafting: extrusion + filling with semifluid materials

The experimental technique—developed in 1998 by Prof. Behrokh Khoshnevis at the University of Southern California in Los Angeles—combines the extrusion technique, applied to the object 'surfaces', to a filler material injected between the extruded faces, thus creating a solid core. The technique is suitable for the architectural scale, as it is much faster than comparable purely extrusion-based techniques, while 'a wide choice of semi-fluid materials could be used, such as polymers, ceramics, composite wood materials, mortar, cement, concrete and other materials, that once deposited by a nozzle are able to quickly solidify and resist pressure from the weight of the structure itself. […] Currently, the Contour Crafting technology can build a 185 m^2 house with all utilities for electrical and plumbing systems in less than 24 h' (**Figure 2**) ([4], p. 119) .

3.2.1.4. Concrete printing

Similar to contour crafting, developed at Loughborough University in the United Kingdom since 2004, it is similar to contour crafting, but allows to control the resolution of the nozzle for the deposition of both bulk materials and fine detail within the same process.

3.2.1.5. Metal extrusion (FDMm)

It encompasses a series of alternative experimental techniques that are either an adaptation of the semisolid material extrusion technique to low-melting-point metal, or the use of gas metal arc fusion welding robots.

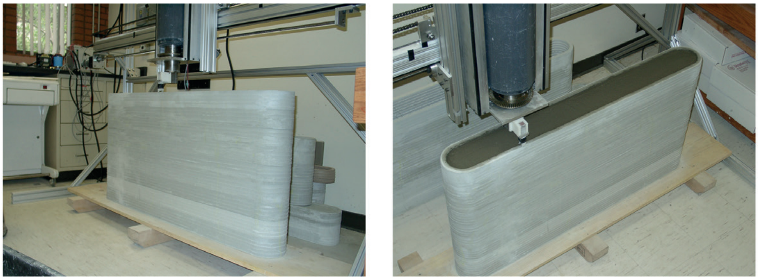

Figure 2. Contour crafting (https://tinyurl.com/y7xsbq83).

3.2.2. Bonding of granular materials

Unlike the previously analyzed techniques, this series of techniques is based on the selective 'bonding' of grains of material previously disposed in an array. The advantage of this set of techniques lies in the almost infinite freedom of geometrical shapes it can produce, since no supports are needed and even nested shapes are printable in one step.

3.2.2.1. Binder jetting

The process consists in a multinozzle inkjet print head moving, layer by layer, on a 'powder bed', previously laid on the build platform. While a sweeper blade or roller evenly distributes the powder across the bed, the head selectively jets a binder solution, which solidifies the powder according to the section at stake. The bed is then lowered layer after layer. Different materials can be used as powder, including originally starch and gypsum plaster, while the binder—mostly water—can also contain dyes and other substances impacting on the physical properties of the powder (such as viscosity and surface tension). 'The resulting plaster parts typically lack "green strength" and require infiltration by melted wax, cyanoacrylate glue, epoxy, etc. before regular handling' ([4], pp. 53–55). The results of such technique tend to lack accuracy.

3.2.2.2. Selective laser sintering (SLS)

The process is generically called 'powder bed fusion', and it uses high-power laser to bond together the particles of material. Similar to the binder jetting process, the process consists in the selective hardening/binding of a powder bed. However, in this technique, the hardening happens through a laser beam that follows the cross section of the relevant layer. The material is heated just below the boiling point (proper 'sintering') or above it (selective laser melting). The process is completed layer by layer.

The main disadvantage of the process is the relatively high cost of the powerful lasers needed to print in materials other than composites, plastics and waxes, and the relatively weak mechanical performance of composite powders suitable for engineering applications. The advantages are numerous, ranging to the already mentioned geometrical freedom, to the fact it does not need much additional tooling after the object is printed. Moreover, the results can be very precise with high resolution (**Figure 3**).

3.2.2.3. Selective inhibition sintering (SIS)

This technique, developed by Dr. Behrokh Khoshnevis and his team at the University of Southern California, tries to address the trade-offs between the cost of high-power lasers for sintering metal, and the weak mechanical performance of composite materials suitable for lower-power lasers. 'In fact the principal innovation behind the SIS technique is the prevention of selected regions of each powder layer from sintering, achieved by operating on the regions external to the part in each layer with a "sintering inhibitor". A commercial piezoelectric print head is utilized to deposit a liquid chemical solution (inhibitor) at the periphery of the part for each layer. When all the layers have been treated, the entire part is removed from the machine and bulk sintered in a conventional sintering furnace. The inhibitor deposited at the part's boundary decomposes

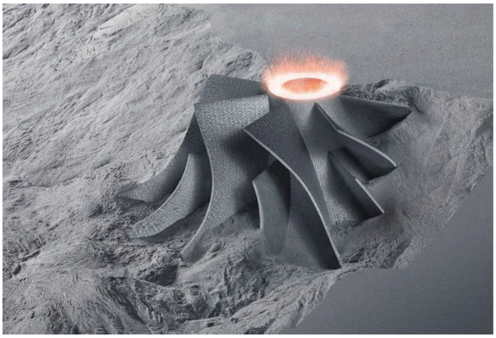

Figure 3. Example of SLS production (https://tinyurl.com/y7bybghk).

into hard particles that impede the sintering process. The particles in this region are prevented from fusing, allowing for removal of inhibited boundary sections and revealing of the completed part. It is easiest to think of the part as if it were encased in a sacrificial mold' ([4], p. 59).

This technique is still experimental, but is promising due to the lower costs implied by the use of conventional print heads available on the market, while it manages to produce full-metal parts with strong mechanical performances.

3.2.3. Photopolymerization of liquid materials

3.2.3.1. Stereolithography (SLA)

As seen, stereolithography was invented in the 1980s and consists in a technique whereby a laser beam selectively hardens a UV-sensitive liquid resin in a vat, following a sequence of cross-sections of the object to be printed. The vat is lowered every layer, until the whole object is printed. The technique was originally intended as a faster and cheaper way to create prototypes for engineers. In fact, the main advantage of such a technique is the high resolution achievable, since it is based on a laser beam. However, because a specific photopolymer resin is needed, it is costly and does not offer a wide array of materials to print with; even tough new materials are constantly added, and may allow the use of such technique not only for prototyping/molding, but also for final objects. In the process, supports are needed and must be removed after the process has ended. Cleaning and other post-processing is needed, including curing in UV-ovens, vanishing or blasting with glass beads.

3.2.3.2. Digital light processing (DLP)

This technique is a low-cost version of stereolithography. It is based on the same principle of photopolymerization, but instead of a laser beam, it uses a video projector in order to harden the resin. A DLP projector is positioned above a resin vat and the resin is hardened layer by layer, as in the SLA. The results are similar to those of SLA, but here, a higher resolution can be achieved on a smaller projection surface, since the projected image has a fixed resolution (the projector's). The process is cheaper and faster than SLA, since, respectively, it is based on common technology (the beamer) and it hardens each layer at once (**Figure 4**).

Figure 4. Example of SLA production (https://tinyurl.com/yal2wluv).

3.2.3.3. Multijet modeling (Polyjet)

This technique is a recent development of previous ones. Developed in 2000 by Objet Geometries (now merged with Stratasys), it combines a print-head spraying liquid photopolymers into very thin layers, and a UV lamp—positioned under the print-head nozzles—hardening each of said layers. Layers are created by lowering the work platform, while the head just moves along the Y axis, since it covers the X axis through a number of nozzles. Supports are needed, and printed with a gel-like material by a second row of nozzles. The process also allows the use of a combination between two materials with a varying gradient, thus allowing to locally customize the material properties ('digital materials'). For instance, a mix of soft and hard parts could be printed together. The resolution of this process is also very high. The main drawback is the limitation to photopolymers as printing material, which is expensive and does not offer enough mechanical strength for some uses (**Figures 5** and **6**).

Figure 5. Carbon/Adidas 3D printed sole (https://tinyurl.com/y7ked3cu).

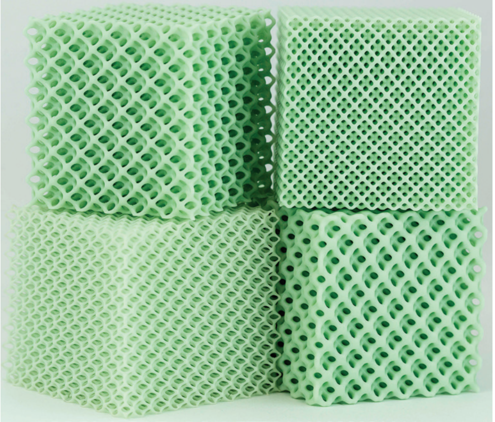

Figure 6. Carbon 3D printed lattice structure (https://tinyurl.com/y8n472bs).

3.2.3.4. Carbon 'digital light synthesis™'

The technique—developed by the 2013-founded company Carbon—uses digital light projection, oxygen-permeable optics, and Carbon's programmable liquid resins and allows printing 'up to 100 times faster than other additive manufacturing processes. […] Carbon's technology is inherently capable of printing high-resolution parts with an excellent surface finish and isotropic mechanical properties'. It allows 'to print unique lattices that can replace materials such as foam in headsets, shoe midsoles, and seating applications. What is especially unique is Carbon's ability to design and make tunable lattices depending on customer application needs. Engineers for the first time can 3D print multiple unique functional zones within the same monolithic part and tune the mechanical properties within each of these functional zones depending on the application requirements' [5]. This technique is unique in the panorama of additive manufacturing, and it is being used by Adidas to print training shoes' soles on an industrial scale with a variation in the material density throughout, so as to obtain the required local performances. It is then a good example of both the possibilities of 3D printing in the industrial production process of finished goods, as well as the revolutionary potential of obtaining different physical performances by controlling the density and structure of the material.

3.2.3.5. Volumetric 3D printing

'A team of scientists and engineers led by Lawrence Livermore National Laboratory (LLNL) has developed a process that uses hologram-like lasers to make complete objects in seconds inside a tank of liquid resin. Called volumetric 3D printing' [6].

In fact, 'two limitations of additive manufacturing methods that arise from layer-based fabrication are slow speed and geometric constraints (which include poor surface quality). Both limitations are overcome in the work […], introducing a new volumetric additive fabrication paradigm that produces photopolymer structures with complex nonperiodic three-dimensional geometries on a time scale of seconds. We implement this approach using holographic patterning of light fields, demonstrate the fabrication of a variety of structures, and study the properties of the light patterns and photosensitive resins required for this fabrication approach. The results indicate that low-absorbing resins containing ~0.1% photoinitiator, illuminated at modest powers (~10–100 mW), may be successfully used to build full structures in ~1–10′ [7].

3.3. Use in the AEC fields

3D printing in AEC can be seen as an opportunity in many ways.

- Direct/indirect (molds).

As we have seen, additive manufacturing is not yet in the stage of fully mature technology, and several new breakthroughs are emerging year after year. This means that there is still a great growth potential, but it also implies that there are still many limitations to overcome, and each currently available technique does not seem to answer many of the needs of industrial production. As to architecture, engineering and construction (AEC), such limitations seem even more problematic. The sheer scale of such endeavors is in fact limiting the kind of techniques that could be adopted to manufacture all or part of a building. Moreover, the requirements for specific physical and mechanical properties—often traditionally obtained through the use of multiple layers of different materials—and the sheer volume of material needed in order to achieve the required performances are other clear limiting factors.

Therefore, depending on the kind of elements to be produced—structural, finishes, etc.—different techniques can be most appropriate. For instance, extrusion of fuse material techniques does not seem appropriate to print huge structural elements, both due to the lack of physical properties and the (low) production throughput.

However, most techniques can be stretched beyond their intended range of production by adopting an indirect approach: for instance, even the said fuse material extrusion techniques can be used to create molds for reinforced concrete structural elements. While scale issues remain, speed and mechanical issues are overcome, since the real structure will consist of the concrete poured in the mold along with steel reinforcements. The main advantage is the opportunity to create, with relative ease, elements that follow complex geometries, which would otherwise be very difficult to achieve, and to do so with great accuracy. Example: ETH mesh-mold, 2014 (**Figures 7** and **8**) [8].

- Modules/components, joints and monoliths.

Scale limitations remain one of the main bottlenecks for the use of additive manufacturing techniques in the realm of AEC.

3.3.1. Monoliths

There are some experimental attempts to create and utilize printing machines that could directly deal with the architectural scale, and ‘print’ entire buildings as ‘monoliths’, i.e., as a unique piece printed at once, and therefore resulting in an almost seamless unique piece of material(s), possibly with isotropic properties.

An example thereof is ‘D-Shape’, a company and technique developed in 2004 by the Italian engineer Enrico Dini, where fabrication is possible on an area of 6 by 6 m and limitless height.

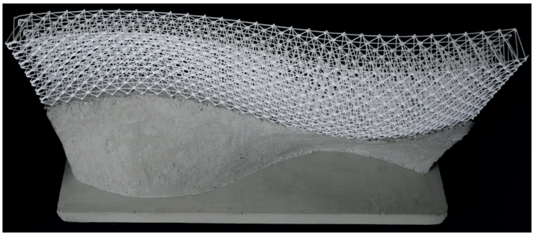

Figure 7. Robotic mesh-molding technique: printed output (https://tinyurl.com/ydddvp4g).

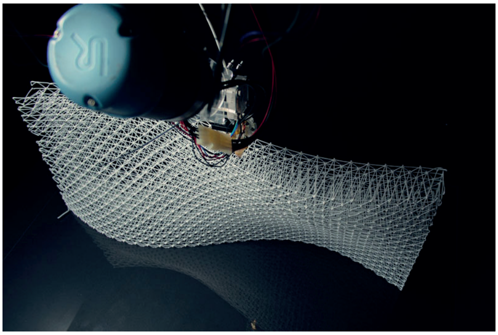

Figure 8. Robotic mesh-molding technique: while printing (https://tinyurl.com/ydddvp4g).

‘Enrico Dini’s printing technique has the great advantage of providing support for overhanging geometries, as sand is selectively transformed to stone within a bed of untouched sand, allowing freeform 3D geometries to be produced. Limitations in this technology are today the strength of materials and printing resolution of approximately 5dpi (20 mm in the X and Y axis and 5 mm in the Z axis)’ (**Figures 9** and **10**) ([4], p. 116).

Figure 9. D-shape printed monolith (https://tinyurl.com/ybdf339t).

Figure 10. D-shape printed monolith (https://tinyurl.com/y8c87o6z).

'Contour crafting' and 'concrete printing' by Loughborough University, as we already saw, are yet other techniques suitable for monolithic production. However, most of the pieces printed so far tend to lack the complexity of freeform 3D geometries, showing a variation along just two of the three axes, thus missing out what is supposed to be one of the main advantages of additive manufacturing. Moreover, concrete printing has been tested with a build volume of just 2 m × 2.5 m × 5 m, which would not fit the required scale for any substantial architectural endeavor.

Besides the specific limitation outlined for each 'monolithic' printing technique, a general criticality lies in the many different kinds of performances required in AEC: mechanical and structural, thermal, permeability to light and air, and the like. Such aspects are traditionally dealt with by a series of different 'layers' of elements made of different materials. Even a basic bearing brick wall does usually incorporate not only bricks, but also a binder, as well as possibly a damp-proof membrane, etc. Similarly, a reinforced concrete structure usually needs specific layers to deal with the propagation of sounds and vibrations, thermal bridges, and many other aspects. At the moment, it does not seem that additive manufacturing techniques can deal with such requirements effectively, or at least there are clear gaps that must be closed by the extensive use of other techniques. The trade-off between printing resolution and speed is another potential hindrance for this approach to become advantageous: in fact, usually in a building, there is a hierarchy among elements as to their functional relevance, and for some of them it is crucial to be produced with high accuracy and isotropy, while for others speed seems more relevant. Until techniques like concrete printing by Loughborough University—which allows for a change in nozzle resolution while printing, thus controlling the trade-off speed-resolution—will not be industrially feasible and reliable, this approach seems reserved to research projects. However, as we will see, in a future stage of technical development, we can imagine that not only speed and accuracy will be dealt with appropriately for the architectural scale, but also that printing with several materials while gaining control over the fine regulation of the material properties—e.g., density, isotropy and material combination—will make the production of monolithic structure not only advantageous, but even necessary for some advanced new ways of building (**Figure 11**).

Example of ‘monoliths’. MX3D bridge, ongoing. For their nature, bridges and other urban infrastructure may have the right scale for monolithic production. Moreover, they may not require the same number of different performances—notably, the thermal performances required in buildings to guarantee the indoor comfort—and thus may well be constituted by even a sole material. MX3D has chosen a small urban bridge in Amsterdam as an opportunity to showcase and test its 3D printing technology, based on ‘multiaxis 3D print technology’, a combination of 6-axes robotic arms and metal depositor-welders tipping the robotic arms. ‘The robots, which are tipped with welders, will construct the bridge in front of them as they go, literally printing welded steel in midair’ [9]. ‘The robot arms are similar to those used in the car industry and they can print metals and plastics from single extruders, as well as combinations of the two materials together’ [10]. Even though the originally planned on-site printing was dismissed to avoid congestion in a crowded area of the city, the printing method is claimed to be able to create the monolithic structure on site and with no supports/scaffolding, which would open interesting perspectives for the whole AEC field (**Figures 12** and **13**).

3.3.2. Modules and joints

Another approach to make the best out of additive manufacturing techniques, especially considering their limitations as of today, is then to use them on a lesser scale, focusing on the specific comparative advantages in creating parts of an architecture.

A first obvious method that has been widely adopted in AEC since antiquity, but especially after the industrialization of the production process, is the decomposition of architectures into modules or components. Such an approach requires that the geometrical subdivision be

Figure 11. Concrete printing (https://tinyurl.com/ydd8lmsa).

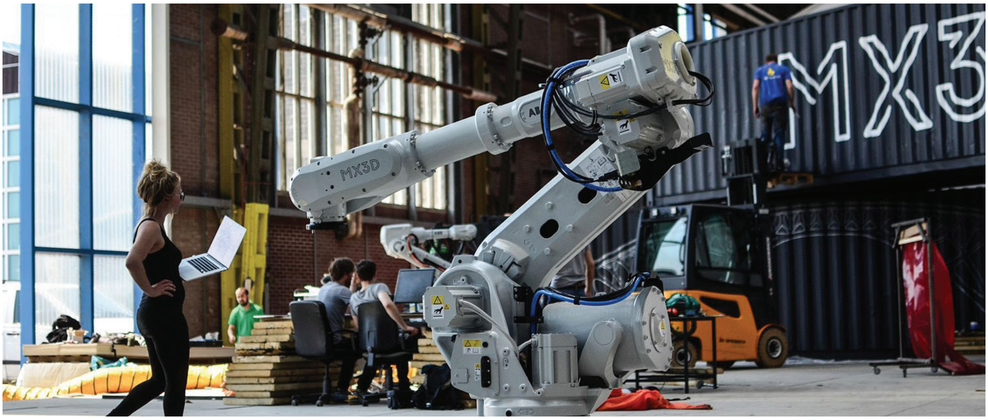

Figure 12. Robotically printed metal bridge (https://tinyurl.com/yalppx2w).

Figure 13. Robotically printed metal bridge (https://tinyurl.com/yanqvhv9).

carefully studied, as discontinuities can constitute weak spots. Moreover, modules need interfaces to be connected to one another, which may imply the need of taking care of multiple layers being connected, while keeping the junction water- and air-tight.

Example: Brian Peters, 2014, 3D printed clay bricks.

'Building Bytes is a project that goes beyond using new tools to make old products. Instead, it follows the additive logic of the printing path—rather than the conventional moulding or extrusion process—to make bricks that are otherwise impractical or impossible to make' (**Figure 14**) [11].

A second area where additive manufacturing seems most suitable is the production of joints. Joints are particularly relevant in many contemporary AEC projects since they allow the creation of freeform, irregular geometries by connecting standardized elements. In other words, joints can 'absorb' the geometrical variation of the overall shape by 'internalizing' it in their spatial configuration. The relevance of additive manufacturing techniques then becomes clear, if we consider that it allows producing a number of alike but different elements (mass customization) at the same cost and in the same time than a series of identical ones.

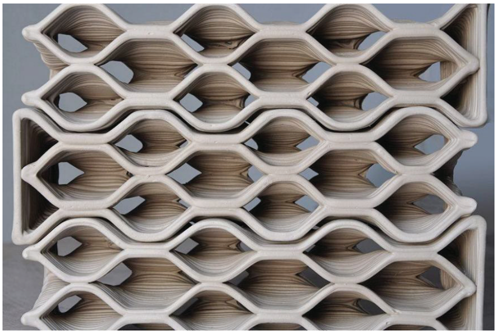

Figure 14. Clay printed modular structure (https://tinyurl.com/yb62v3cz).

There is more to it: joints typically perform key structural functions, and thus are subject to intense stresses. While this aspect seems to rule out many 3D printing techniques due to the weakness of available materials to print with, the customization of each joint's geometry to meet its specific performance targets can be a crucial success factor of additive manufacturing techniques, allowing optimization techniques such as topology optimization. It is in fact only 3D printing techniques that can give birth to topologically optimized objects with their highly organic and irregular shapes, including voids that would be often impossible to obtain with any other production technique.

Example: Arup, Optimized Structural Element (nodes), 2014–2015 (**Figure 15**).

The engineering company has successfully produced building structural elements through additive manufacturing, which are an optimization of a standard node for a tensegrity structure. A paper showing the results of the study explains that: 'Based on these initial results the design process was fine-tuned focusing on product integration and improved control of the optimization process. A full set of material tests was executed which should lead to a certification process required for specifying AM-produced products in the Building Industry' [12].

The ability of printing parts that are nested within each other opens up further relevant opportunities for the creation of movable joints. While with traditional techniques, such

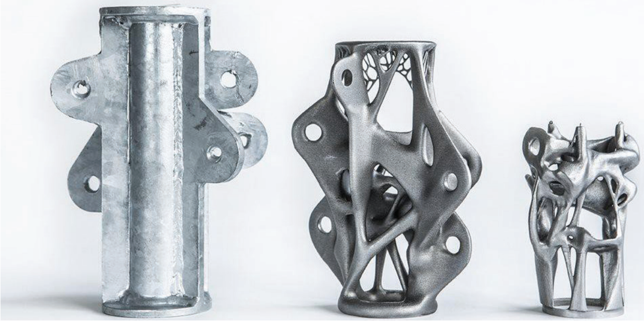

Figure 15. Topologically optimized 3D printed metal nodes (https://tinyurl.com/y9kx2o7l).

joints could be created only by welding together parts of the joint—which increases the risk of potential discontinuities and weaknesses—the new approach can produce more uniform pieces of isotropic material (**Figure 16**).

Example: Master Thesis at ACTLab by G.Rossi, 3D printed interlocking structure.

- From fast prototyping to 'the real thing'.

The great hype lately surrounding 3D printing and additive manufacturing in general is not only due to the opportunity offered to create complex shapes under the direct control of computers—this has been the case for the last 50+ years in many industrial sectors, such as automotive—but is rather rooted in the now possible production of final construction elements instead of mere rapid prototyping. This evolution has required, and will further require, advancement as to the type of materials that can be printed with, as well as in the tolerances that can be achieved with every new technique, along with the overall quality of the output, including isotropy and other physical/mechanical characteristics.

Working with a rapid prototyping paradigm usually implies that each prototype is tested and then mass-produced in a series of identical copies when the required performances are achieved. On the contrary, using additive manufacturing as a tool for production, it is now possible to create 'final' elements that are different from each other and are produced directly as they are simulated in the software. The tighter correspondence between the virtual modeling and the real output means that—while prototyping remains useful to have some hard data to back the simulations up—most simulations can be now close enough to the real behavior of the printed elements as well as of the overall performance of the structure with no need to prototype each and every element first. Moreover, while using additive manufacturing for prototyping and a different kind of production for the final elements can create a mismatch between the two, the direct use of 3D printing techniques for final production allows to directly harvest the benefits of the technique. The recalled example of Adidas 3D printing shoes' soles is certainly an interesting reference as to the industrial potential of the technique, while the adoption of similar models in ABC at the moment is still mostly in the framework of research.

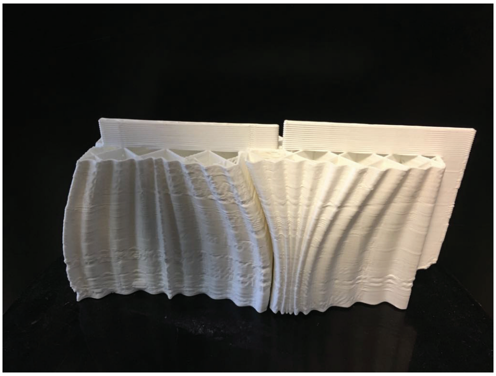

Figure 16. G. Rossi at ACTLab, 3D printed interlocking structure (credits Politecnico di Milano University).

Example: GE, 2015, fully 3D printed mini jet engine.

This project, which lies entirely within the field of engineering, shows how far additive manufacturing techniques have gone over the last few years. The engine, which could serve a radio-controlled small plane, has been 3D printed using the direct metal laser melting (DMLM) technique. It was then assembled by hand, and is fully working (**Figure 17**).

3.4. Current impact on design/production paradigms and case studies

- Mass-customization and the ideal match with parametric generative design within the computational design tools.

Additive manufacturing, being a production method transforming the 'virtual' 3D model into a real thing with a comparable cost per volume printed, allows for a wholly new approach to design and fabrication. While the First and Second Industrial Revolutions, as seen, required as much standardization as possible, it is now possible and often preferable to design each element specifically optimized for the function and position it holds within a structure. For instance, façade-shading elements need not be all equal if their position between the sun path and the spaces to shade is different.

In order to exploit this potential fully, however, it would be impractical to design each element one by one: besides being time-consuming, it would possibly be also difficult to calculate and draw by hand what the right geometrical configuration of the said shading elements should be, since the sun path changes over time. Luckily, given the 'direct' creation of any shape from the 3D virtual model, it is enough to devise a system that allows the creation of a series of elements—e.g., our shading element, in the example—that are similar in design and function, but have the right measures for the specific place they are intended for. In other words, we need a tool that—given a set of geometrical and logical relationship between the required performance and the given constraints—could generate a series of optimized elements. Such a tool can be found in the computational design realm, specifically in generative algorithms, where the final shape is generated by the software based on the logical connection and operations between the provided inputs. 'Form is differentiated from the fundamental principles

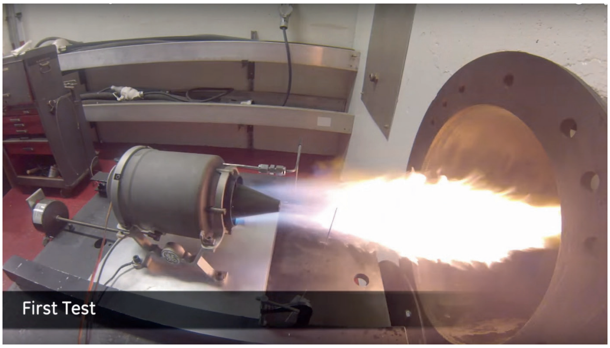

Figure 17. GE fully 3D printed working engine prototype (https://tinyurl.com/y85355af).

organizing the different elements within the manufactured component. None of the components is considered as an ideal primary model; every element might differ in geometry and form as long as the intricate logical interrelations are accurate. The bigger the variation and the complexity, the higher is the value and the benefit of using an AM machine' ([4], pp. 23-24).

The output of a mass-customization process is then the creation of a series (mass) of industrially crafted objects, which are nonetheless tailored (customized) on the specific place and functions they must perform. If duly performed, such a process can yield specific performances while possibly costing as much as standard elements and using only the material needed.

Example: Politecnico di Milano, Expo 2020 Desert tectonics hypothesis. 3D printed external shading structure in HTPLA + Sand (**Figure 18**).

- Nested and interlocked geometries otherwise impossible to be produced.

Besides movable joints, many other interlocking geometries can be now produced, which would have been at least very complex to craft without AM techniques. Chains, textile-like structures and the like are all examples of interlocking geometries that are usually obtained by knitting thread-like materials, or else require heavy hand crafting, as in the traditional chainmail.

Example: Gürcüm, 2017, textile-like structures.

This study synthetizes the possibilities offered by AM in this area, discussing 'the important properties of traditional fabrics that are to be expected of 3D printed structures namely physical properties like flexibility, bending and and drapability' (**Figure 19**) [13].

- Design from simple 'shape-drawing' to simulation based on material physics and static embedded fabrication constraints.

Traditionally, drawing techniques have been used by architects to communicate their project to a series of other professional figures, such as engineers and site managers, in order to have it checked and realized. The shape of buildings and elements thereof was usually devised by the architect in the early design phases based on a rough understanding of the underlying physical characteristics and required performances, and would be further adapted in case the design proved to be impractical to realize. Things have now changed, since it is now possible to include within the design phase a simulation of the physical behavior of the specific shapes based on the specific material characteristics. Therefore, computational design techniques do not just 'represent' a pre-conceived idea of shape, but can allow to reach a shape as the result of a process that incorporates many performance and material constraints, including fabrication constraints.

Example: L. De Sanctis, 3D printed clay brick. The underlying idea of this project was 'to develop a customized design of a very traditional building component: a clay brick. The concept relies on the possibility to have a flexible system of tile modules, which could be site specific and ad hoc buildable with Additive Manufacturing (AM) in relation to the context. The design of the component is developed analytically with respect to a framework of requirements and performance typical of a clay component, with the addition of standard features of a wall system […] An algorithm developed with the use of Grasshopper and Python has been applied to determine the wall thicknesses and amount of material distributed, while optimizing structural performances of a design and considering production constraints. It has

Figure 18. Politecnico di Milano, expo 2020 desert tectonics hypothesis (credits Politecnico di Milano University).

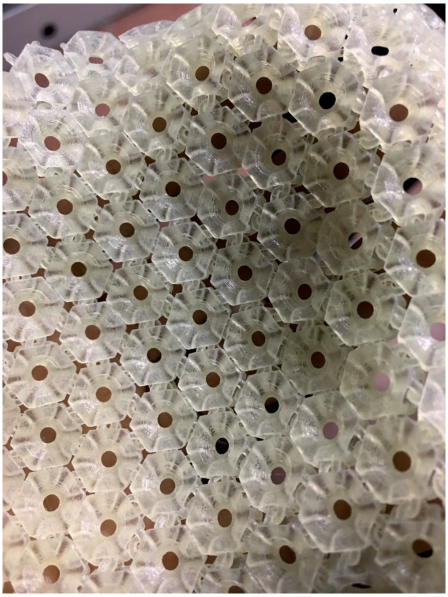

Figure 19. Example of textile-like 3D printed interlocking structure (credits Politecnico di Milano University).

thus been identified as an ideal format (similar to what exists in trade), and compatible with printing constraints, a dimension of 250 × 250 × 120/125 mm. This dimension could also fit within exiting insulating EPS panels (500 × 1000 × 50 mm), integrated with electrical pipes of 8 mm or junction box of 120 × 100 × 70 mm. Another advantage of this system is the possibility of integration within any kind of form or structure, in relation to its use. Due to the necessity to preserve structural equilibrium within a wall, design of cantilevered parts of the brick has been performed within the mass quantity not superior to 40%' (**Figure 20**) [14].

- Optimized and multiperformative shapes as the result of topological optimization and multifactorial design constraints and analysis. Performative biomimicry.

As seen, additive manufacturing allows the designers to potentially craft each and every element of an architecture all different from each other. Printing 'topologically optimized' elements seems one of the most valuable opportunities offered by AM. 'Topological optimization is a mathematical approach that aims at optimizing material layout within a given design space, for a given set of loads and boundary conditions such that the resulting layout meets a prescribed set of performance targets. Topology optimization software systematically analyzes the stresses on these shapes and then removes the most superfluous material from the design. This process is repeated over and over by the software until the target amount of material is reached, and by the end the computer design leaves only a skeletal structure. The advantage of parts made with topology optimization is therefore that the same strength characteristics can be created with less material, and this yields a greater strength to weight ratio, an important property across most industries, from automotive, to aerospace, but also architecture and building construction' ([4], p. 157). 'As a practical example, structural rib elements in an Airbus wing designed with topology optimization saved over 500kg in structural weight, which translates to significant cost savings' [15].

Example: R. Naboni at ACTLab, cellular solid lattice structure in pla.

The project combines and applies the principle of topological optimization—deposing material only where it is needed for structural reasons—to a system of load-responsive interconnected struts made of polymeric material. The result is a custom lattice microstructure defined as functionally graded lattice structure, with spatially varying characteristics. 'Algorithms for topology optimization of freeform shapes are employed to determine the material organization as well as a performative matrix […] The potential of this system relies on its implicit resistance

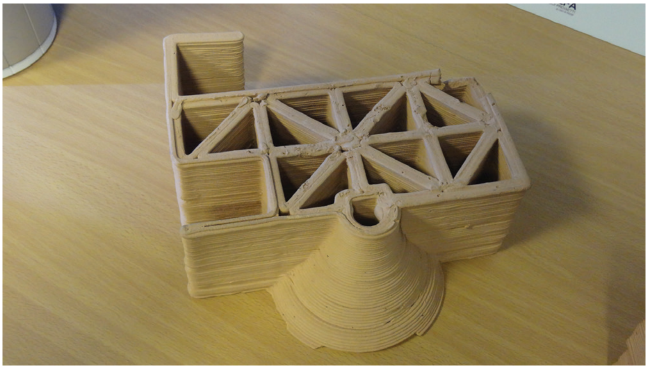

Figure 20. L. De Sanctis, at ACTLab, 3D printed custom clay brick.

Figure 21. R. Naboni at ACTLab, topologically optimized cellular lattice structure.

Figure 22. Neri Oxman, multiperformative 3D printed chaise-longue (https://tinyurl.com/y8f3d6t9).

and reduced use of material, combined with the possibility to adapt to any architectural shape. They are composed by an interconnected network of struts, pin-jointed or rigidly bonded at their connections. At one level, they can be analyzed using classical methods of mechanics, a typical space frames, on the other side, within a certain scale range, lattice can be considered as a material, with its own set of effective properties, allowing direct comparison with homogeneous materials. Mechanical properties of lattice materials are governed, in part, by those of the material from which they are made, but most importantly by the topology and relative density of the cellular structure. This methodology requires the description of custom algorithms to generate lattice structures parametrized on the base of a continuous feedback loop from a Topology Optimization and manage the additive process of materialization' (**Figure 21**) [14].

Example: Neri Oxman, 2014, Gemini Alpha Chaise Longue.

The inner skin is made of three different rubber-like plastics, printed by a Stratasys' new Objet500 so as to obtain 44 different composites. Each of these composites has a different rigidity and color, and is arranged in a way to cushion the user. The choice of shapes is also informed by their noise-cancelling properties. The chaise is supposed to create a silent and calm environment inside, through the combination of a concave shape reflecting sounds inwards and of the inner surface geometry and materiality, which scatters and absorbs the sound waves (**Figure 22**).

3.5. Future perspectives

3.5.1. Potential issues

- Safety certification and accountability (given the 'exotic' nonstandard geometries and the extensive reliance upon software simulation).

One major issue with not only additive manufacturing, but in general any nonstandardized manufacturing, is the implied impossibility to test each and every item produced. This does not constitute a problem in case every set of produced items is exactly the same, since it is enough to test one for testing them all. However, it would not be feasible or at least in sharp contrast to the very same aim of mass-customization—adaptability at a cost comparable to that of standardized solutions—to test all produced items. As already noted, the solution which is usually adopted is to sample-test within the range of produced items, trying to select the right samples along the range. Such process has to rely on the implied correspondence between the virtual and the real, and therefore the specificities of each printing technique have to be accounted for in the software in order to properly simulate the real-world behaviors. For instance, the typical anisotropy of most extrusion-based printing, and the differences in physical/mechanical behaviors along different directions must be factored-in. The process also heavily relies on software-based automatic check about most required performances, e.g., mechanical. The software's results will then depend both on the selection of data that are fed into it, as well as on the reliability of the software itself.

All these issues raise questions about the accountability for any failure of the printed elements, and will probably require a whole new set of legal tools to sort out who is accountable in each case, and where to draw the line between unforeseeable circumstances, due diligence and lack thereof.

- Optimization vis-à-vis resilience, future adaptation and available architectural langwuage.

Abandoning the paradigm of standardized production for embracing a more and more optimization-driven approach seems a great innovation in view of wasting less material and achieving more with less at the same time. Any structure where the quantity and the structure of the deposed material is optimized to the prospected performances seems like a perfect way to mimic nature and its efficient adaptive behaviors. However—at least until the output of additive manufacturing technique will be re-configurable—3D printed objects, unlike natural living beings, tend to be fixed once and for all, unless additions or modifications are purposively performed. However, such interventions *a posteriori* could clash with the optimized existing (macro- and micro-) geometry, which is based on the specific data and constraints that were decided at the original design and construction time. In fact, such issue holds true for any AEC endeavor where tolerances and redundancies are kept at a safe but minimal level. However, in traditional constructions, the material is usually distributed in a more constant and uniform fashion, so that any slight change to the conditions and constraints might have a less radical impact than on a structure where the material is reduced in quantity and fine-tuned on more specific conditions.

Moreover, also the sheer lack of standard ‘interfaces’ to join additional elements could be a limiting factor for the adaptation of the structure to new conditions over time. It is quite evident that adding a new row of bricks to a parallelepiped-shaped wall is a much lesser feat than to an Enrico Dini’s organic structure.

All this implies that the short-term sustainability of an optimized 3D printed structure could be disadvantageous to the long-term adaptability and resilience of it. A 3D printed structure could be so costly and challenging to adapt, that it might be even cost-effective to tear it down and re-build from scratch. The obvious question is whether such an approach could prove more sustainable at all, and it is wise to imagine that designers and architects will have to include future adaptability within their design thought process, goals and constraints.

Lastly, as regards the architectural language, the use of constraint-based, parametric generative design based on physical properties of materials could raise concerns about the risks of adopting an architectural ‘language’ as a mere by-product of the chosen design tools. This would also imply that—those tools and techniques being common among designers, and being physical laws constant in time—the formal output of all design processes by different designers and architects would tend to be really similar, if not identical, among each other and over time. This ‘end of history’, whenever had to become a reality, would of course contradict the essence of millennia of architectural development and the idea of evolution itself. However, it seems reasonable to believe that creativity can and will be shifted to setting the constraints, the performance goals and even the formal relationships that should characterize the space in the view of each architect.

3.5.2. Potentialities

- Multiscalar optimization: from the microscale of materials to the macroscale of architecture.

While, as seen, topological optimization techniques have been already widely used to fabricate a wide range of optimized components and objects in architecture and design, it is still at the level of research that similar optimization methods are adopted as to the microscale of materials. In fact, it is usually the case that topologically optimized shapes are printed with constant material density and composition. ‘Most such technologies, however, remain limited to producing single-material, constant-property prototypes from a restricted range of materials’ [16]. However, such dualism between the micro- and the macroscales could be surpassed in the near future, since 3D printed structures could be not only topologically optimized at the macroscale, but also at the microscale, both as to density and structure of material, and as to material composition or combination. This would resemble what happens in nature, where the microstructure of plants and other living beings tends to correspond to the required local performances. In fact, ‘Since many biological materials are made of fibrous heterogeneous compositions, their multi-functionality is typically achieved by mapping performance requirements to strategies of material structuring and allocation. The shape of matter is therefore directly linked to the influences of force acting upon it. Material is concentrated in regions of high strength and dispersed in areas where stiffness is not required’ [16].

Such an opportunity would be a game-changer in AEC. A completely different design paradigm would be needed, since materiality would not be determined *a priori*, as a given property of a commercially available material. Rather, material characteristics—including composition, density and structure—could (and would have to) be engineered as a part of the overall design. Also, the typical discontinuity between micro- and macroscales would have to be reconsidered, since a continuum could be envisaged, similar to a fractal geometry. 'A bio-inspired fabrication approach calls for a shift from shape-centric virtual and physical prototyping to materialcentric fabrication processes. In this approach, not unlike he bones' remodelling process (**Figure 7**), the distribution of material properties is informed by structural and environmental performance criteria acting upon the component, and contributes to its internal physical makeup. It thus requires a set of virtual and physical prototyping tools and methods that support a variable-fabrication approach, not unlike Nature's' [16].

Voxel-based materials (and printing techniques) would be, in this perspective, another important step forward in such a direction. 'We expect digital materials and the 3D printing thereof to provide unprecedented control over all aspects of bulk materials in diverse fields ranging from micro scale biological tissue constructs to macro scale building projects. The ability to print multiple materials with incompatible processing characteristics and "smart" voxels with specific electrical, mechanical, or fluidic functionality will enable highly functional composite materials to be printed in a simple, robust fabrication process. Over the last few decades, many technologies have benefited enormously by the transition from analog to digital, and we expect the same for three-dimensional matter' ([17], p. 246).

- Multidimensional design: 4D printing and the inclusion of time and other dimensions to Euclidian geometries.

The shift toward a new production paradigm, where the change in material and material properties is seamlessly possible could open even further opportunities in AEC. In particular, the right combination of materials and material structures can be exploited—according to virtual simulation in the software—to engineer elements, which would behave differently vis-à-vis external conditions, thus determining a change in the overall shape. In other words, the designer could aim for a change of the object shape over time, triggered by some external physical parameters, such as humidity, or temperature change. Similar techniques, which at the moment are still very limited and experimental, have been called 4D printing, with time being the fourth dimension. A pioneering research on the topic has been conducted at MIT's Self-Assembly Lab by Skylar Tibbits, with a specific interest in creating self-assembling shapes [18]. Further research looks at the natural world, especially to the botanical world, in view of creating self-adapting structures: 'Inspired by these botanical systems, we printed composite hydrogel architectures that are encoded with localized, anisotropic swelling behaviour controlled by the alignment of cellulose fibrils along prescribed four-dimensional printing pathways. When combined with a minimal theoretical framework that allows us to solve the inverse problem of designing the alignment patterns for prescribed target shapes, we can programmably fabricate plant-inspired architectures that change shape on immersion in water, yielding complex three-dimensional morphologies' [19].

The use of elements that change over time, adapting to environmental parameters and without any energy requirements or sensors/actuators, could have a profound impact on architecture.

For instance, it is easy to imagine a façade, which would adapt to sun and humidity and provide optimal internal comfort without the need of a complex, fragile and expensive system of sensors and actuators.

As an example thereof, a prototype of a hygroscopic element that opens and closes reacting to air humidity has been 3D printed and successfully tested by a team of researchers. It could constitute a self-adapting, tunable façade element that does not need neither sensors, nor actuators or energy sources other than the mere change in the environmental conditions. The 'research aims to enhance wood's anisotropic and hygroscopic properties by designing and 3D printing custom wood grain structures to promote tunable self-transformation. […] A differentiated printing method promotes wood transformation solely through the design of custom-printed wood fibers. Alternatively, a multimaterial printing method allows for greater control and intensified wood transformations through the precise design of multimaterial prints composed of both synthetic wood and polymers. The presented methods, techniques, and material tests demonstrate the first successful results of differentiated printed wood for self-transforming behavior, suggesting a new approach for programmable material and responsive architectures' (**Figures 23** and **24**) [20].

- Correspondence virtual-real as implicit requirement for a reliable simulation and appraisal of mass-customized, i.e., nonstandard, elements. Applicability of artificial intelligence as possible solution to the impasse of safety certification of nonstandard elements, as well as performance tuning.

The tighter the correspondence between what is being simulated in the virtual realm and what is actually manufactured through 3D printing makes it possible to make assumptions about the performances of the produced pieces. In fact, through sample testing along the range of outcomes, it is possible to validate the virtual simulations about the whole series being manufactured with an acceptable margin of error, possibly with no need to test a sample for each and every shape. Moreover, a feedback loop can help in further perfecting the accuracy of the simulations, attuning them to the specific material and printing machine.

- The reclamation of the continuous variation in architecture as both biomimicry—hence efficient multiperformative holistic solution—and as an expressive potential.

Allowing architects to design structures which could be continuously changing from the micro- to the macroscale, without having to repeat standardized identical elements, would enable architecture to overcome one of the main criticisms that has been raised since the dawn of industrialization: the loss of those ever-changing spatial qualities which natural refuges—such as caves—and hand-made architecture embedded. Some author ([21], p. 81) noted that 'the "informal" of caves, their anti-geometric character, is transmitted to the "barbaric" culture of the proto-Italian settlement, from Pantalica to Barumini, continuing until our times in the grandiose stone complex of Matera'. Those characters would correspond to those spaces human beings evolved in, and that therefore are programmed to appreciate. Notoriously, the issue of standardization in industrialized architecture was already raised more than a century ago, when authors such as John Ruskin criticized the lack of differentiation among industrially produced architectures, preferring the richness of the nuances provided by historical patina and handwork. '[…] The forms and mode of decoration of all the features were

Figure 23. Correa et al., 4D printed adaptive component: when closed (https://tinyurl.com/yd7dy728).

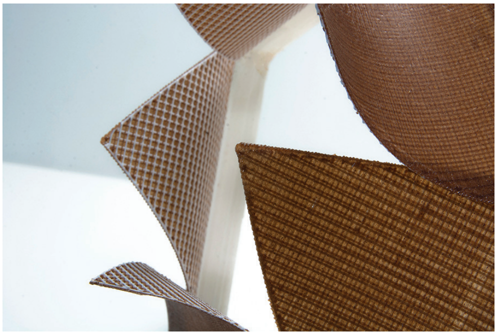

Figure 24. Correa et al., 4D printed adaptive component: when open (https://tinyurl.com/yd7dy728).

universally alike; not servilely alike, but fraternally; not with the sameness of coins cast from one mould, but with the likeness of the members of one family' [22]. The new production techniques, along with parametric design tools, could mimic nature and hand-making also under this respect, creating a spatial experience more nuanced along a continuum of varying shape and materiality. However, as already noted, this becomes a further challenge for the architects, who need to rethink even their own role and tasks in order to make full and best use of such opportunities.

Example: Digital Grotesque—Hansmeyer, Dillenburger, Zurich, 2013.

This case study does not purport all the advanced materiality and scale-free features we are discussing, but is noteworthy as it shows the degree of continuously varying detailing along a shape. 'Digital Grotesque has been designed through an algorithmic procedure called "mesh-grammars", which procedure consists of rules that articulate the structure out of a primitive input form, by recursively splitting surfaces. The process allows for highly specific local conditions with complex topologies to be generated. […] The resulting form, consisting of a mesh of 260 million individual facets, has a resolution and level of detail that would be impossible to specify using traditional means, whether drawn by hand or mouse. It provides a glimpse of the potentials of additive manufacturing' (**Figure 25**) [23].

Figure 25. Hansmeyer Dillenburger, digital grotesque (https://tinyurl.com/yar5udbj).

4. Conclusions

While additive manufacturing has been around in its main techniques already for some 40+ years now, and cannot be considered an immature technology, it is still undergoing a significant innovation process, often through the hybridization of established base-techniques. Furthermore, in its use—especially within the AEC field—its disruptive potential has yet to be exploited and harvested outside the experimental research or pilot projects.

While waiting for 'the ultimate' technique, some limitations of additive manufacturing can be dealt with through a series of smart strategies. One of these consists in limiting its use to only the parts that need customization, so as to overcome the slower production speed still often associated with AM: very often, it is the nodes that can embed the nonstandard, varying part of the overall geometries, thus allowing for the standardization of all other elements. Another strategy consists in the use of such techniques as an indirect means to support other techniques, as it is the case with 3D printed molds to help create freeform concrete structures. In any case, as it is already the case in some fields like engineering, also within AEC it seems that now additive manufacturing techniques can slowly be adopted not only for rapid prototyping of models and components, or as a mere support technique to other more established techniques, but also to produce functional elements within the final, built structures, or even fully functional entire structures.

The adoption of AM techniques in AEC seems likely to bear some lasting consequences going beyond the 'technical' aspects. In fact, similar to how the invention of press systems changed the role of writers and their professional position, or the recording of sounds created a wholly new environment for musicians, so could additive manufacturing produce a lasting impact on the entire world of AEC, especially as regards the role of the architects and the expressive potentialities opened to them.

On the one hand, it is possible to hypothesize more cost-effective outcomes just by the reduced use of materials and working hours granted by the use of these techniques, as for instance topological optimization, form-finding and other computational design techniques. However, such an approach requires that the architects be aware of the underlying geometrical and physical issues and material properties, both in order to create the final shapes—e.g., as a result of constraint-based design approaches—and in view of 'guaranteeing' safety and durability/resilience.

On the other hand, it is now possible for architects to regain a wide degree of autonomy (lost with industrialization) as to the creation of nonstandardized elements and custom 'materials', yet within an industrial mass-customized production process. In other words, while the immediate opportunities opened up by AM techniques seem linked just to faster and cheaper production of possibly unconventional and nonstandardized shapes, the greatest opportunities in AEC could lie in the freedom for architects to explore and imagine new languages and solutions that could be at the same time multiperformative in nature, considering multiple constraints and functions, and spatially inspiring.

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