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From rapid prototyping to building in real scale: methodologies for upscaling additive manufacturing in architecture

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Abstract

The manufacture of architectural components mediated by computer-controlled Additive Manufacturing (AM) technologies has highlighted several positive aspects of their application, namely by enabling customised design solutions and high-performance complex geometries. Taking into account the experience of the Advanced Ceramics R&D Lab, in the production of small- / medium- scale prototypes, this paper explores the main variables and constraints of the production of real-scale architectural components. This information points to a set of procedures that should be avoided and others that should be privileged, allowing to anticipate how AM can contribute for the achievement of high performance components on a large scale.

Keywords: 3D printing, additive manufacturing, material extrusion, LDM, parametric design, computational models.

1. Introduction

From the 1960s onwards, a set of Additive Manufacturing (AM) technologies were applied in the most diverse industrial areas, from aeronautics to aerospace, from automotive to naval, etc. On the one hand, in these sectors, these practices demonstrated versatility, and when combined with processes of Digital Fabrication (DF), a remarkable capacity for optimization and potentialization of the technical capacities that the industries already had, on the other hand, only in the transition to the XXI century those processes started been applied in the architectural and construction industry, sectors that are traditionally more conservative in the integration of innovative technologies.

It is widely recognized that the introduction of digital tools in architectural design allowed an evolutionary change in design and construction methodologies. This reformulation in which architects master digital techniques and technologies, represents a paradigm shift that is often manifested in the emergence of new formal solutions, controlled through the use of computational and parametric design principles. In parallel, principles of mass customisation fostered over the last decades by the use of DF covers not only preliminary design phases, but also seeks its adequacy in the construction itself. In this field, computer-controlled AM is one of the most auspicious production methods.

2. Context

One of the first references to the potential of AM in construction arise in the mid-1990s by Mitchell and McCullough (1997) under the term "Incremental Forming". Often referred as 3D printing, these processes allow an "object" to be obtained from the successive addition of layered material, revealing a sustainable and a very cost effective method due to the fact that material it will be placed exclusively at the places required, by opposition to subtractive processes or traditional techniques of extrusion on mold which, in addition to revealing a high degree of waste of raw material, do not allow customisation.

Currently, AM technologies are readily available for the production of small components, on the 'desktop' scale, however they still not represent an effective solution for the scale of the building. In recent years there has been an increasing number of entities – academic institutions, researchers, builders, architects, engineers, software and hardware companies – that have been concentrating efforts on the application of AM techniques in architecture. This investment resulted in a wide range of prototypes and experiences, as well as in the proposal and development of new manufacturing methods. Each of them introduces new possibilities, new materials or changes in the production process, resulting in the advancement of technology and what can be achieved with it. Yet, despite the recognition of sustained experimentation and knowledge, there are still difficulties in shifting scale and its application to common constructive contexts. It is therefore necessary to understand the implications of these changes and develop solutions that meet the sustainability of their use.

3. Methodology

Considering the paper objectives, an analysis of the most relevant experiences was carried out in order to map the different approaches that are being taken and to frame the potentials and limits of these methods for, finally, better understanding how they can be successfully integrated into architecture.

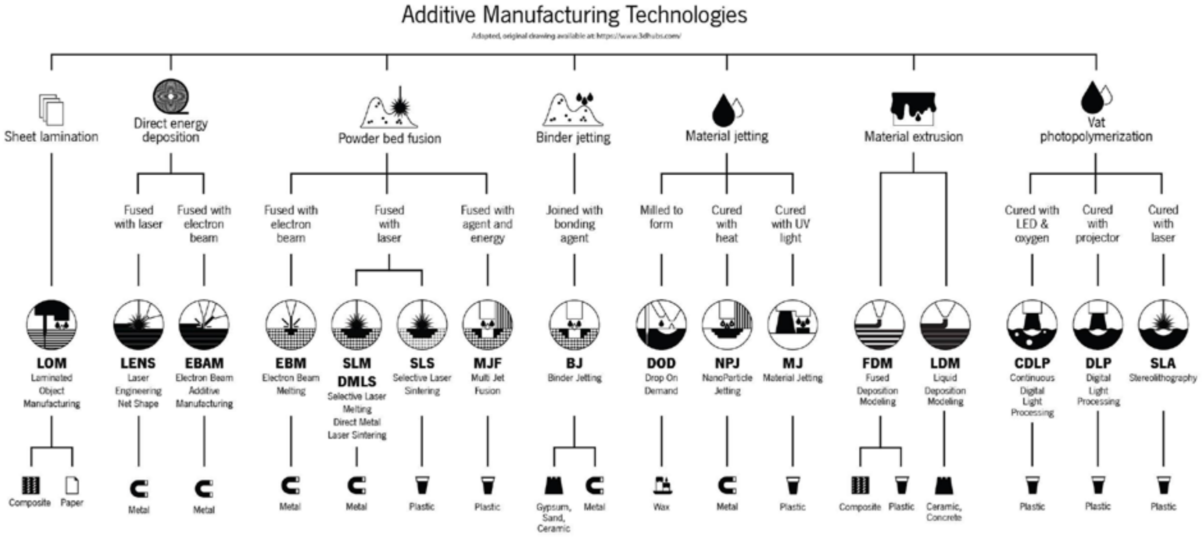

Figure 1: Additive Manufacturing Technologies [Adapted, original drawing available at: www.3dhubs.com]

Although all AM processes follow the same generative principle - three-dimensional geometry is obtained by successively layered material overlapping - it is possible to detect substantial differences in the way this is done. For this registration and the knowledge of several possible approaches, it was adopted the hierarchy used by 3dhubs.com, an online portal specialized in AM [2]. The next scheme synthesizes all the seven techniques (Figure 1).

Given the context of our research being the Advanced Ceramics R&D Lab (ACLab), a research laboratory focused on the AM extrusion technologies in architecture [3], this paper focuses essentially in those processes which can be divided into two topics, "The scale of production" addressing the issue of the scale of manufacture, the support and the size of the objects fabricated, and the "Control of the manufacturing process" seeking to understand how to improve the quality of the object produced as well as develop ways to exponentiate the limits of the technology.

4. Material Extrusion

Material extrusion is the most widespread process of AM due to its ease of use, cost and maintenance. The most common are desktop printers with Fused Deposition Modeling (FDM), also called Fused Filament Fabrication (FFF) prepared to extrude thermoplastics filaments or grain.

Liquid Deposition Modeling (LDM) technique, which was added to the original scheme (Figure 1), reveals a very similar manufacturing process. This nomenclature, proposed by Rosenthal et al. (2018) for the extrusion of paste-like suspensions made from ground beech sawdust and methylcellulose dissolved, was adopted at ACLab to denominate the process of ceramic paste extrusion due to the fact of the feedstock is not heated but successively extruded into layers in the form of a paste having a controlled degree of plasticity.

Contrary to the prior technique where the extrude polymer solidifies instantly due to the temperature drop down, viscous materials such as ceramic and concrete continues to react and the fabricated object undergoes a curing/drying phase (in the air or in a greenhouse). This is a major constraint, however, being a suitable process for almost all types of materials, as long as they make extrusion possible, the ease of use of traditional materials – cement mortars, ceramics or other composite materials – makes it particularly appealing for the construction industry. Thus, most of the experiments carried out with large-scale 3D printing, which will be analyzed next, use extrusion techniques of the raw material in the "liquid" state.

5. The scale of production

The ability of transposing AM techniques at the scale of the building represents a major issue for its application to the construction industry. In this sense, the dimensions and mechanisms of the extrusion apparatus and the reaction of the material are the main constraints. The principle of depositing the layered material assumes that the manufactured object fits within the working area of the 3D printer. For this there are two approaches that can be taken: (1) Continuous deposition manufacturing – Scaling the printing apparatus; (2) Manufacture of discrete elements – Scaling the components to the available print area.

5.1. Continuous deposition manufacturing

Continuous deposition manufacturing aim the direct transposition of techniques of prototyping of small objects to the scale of the construction. This method assumes that the printer's work area is equal to or greater than the building area (of a single element). In this case two approaches have been identified: (1) to increase the size or (2) to enlarge the coverage of the printing apparatus. Both types have already been tested in some exploratory projects.

The work of Behrokh Khoshnevis, creator of the Contour Crafting (CC) process and founder of a company with the same name, is directly associated with the first experiences on the use of large gantry structures that support and move a concrete extrusion system. Khoshnevis demonstrated the possibility of applying AM to a single house or colonies of buildings, may be automatically constructed as whole structures, embedding in each building all the infrastructures during de process [4]. More recently, the printer manufacturer WASP, in the Shamballa Technological Village project, developed a manufacturing system through a Delta-type printer installed on a 12 meter high hexagonal structure [5]. There are many other strategies, however all of them despite valid experiences, these are strongly conditioned by the size of the machinery. The need for a static larger printer machine than the intended object, from certain dimensions, proves to be an unbearable strategy.

Therefore, the approach taken by a research group of the Institute of Advanced Architecture of Catalonia, under the guidance of Sasa Jokic and Petr Novikov, sought to overcome this dichotomy increasing the reach of robots. The apparent need for larger machines than the construction itself was solved with the use of *"minibuilders"*, a small-scale, locomotive robot family that can work simultaneously on the same object. According to the authors, with this method of continuous and coordinated deposition between the different machines, it becomes possible to manufacture objects much larger than the machines [6].

5.2. Manufacture of discrete elements

Most research groups or corporations interested in testing AM technologies in construction end up following a line of thinking that is based on discrete elements. In this approach, instead of requiring a machine that provides a larger work area than the building to be built, it is proposed to adjust the size of the different parts according to the physical characteristics of the machinery (the 3D printer work area, the size of the kiln if necessary, etc.). In this way, there is an approximation to traditional building systems based on three moments: (1) the various constituent components of the building are prefabricated with smaller dimensions; (2) transportation to the work site; (3) Assembly in their positions, creating larger structures.

In relation to the component manufacturing, the boundaries of the machinery or the printer's work area must inform the design. When the aim is discretization, a previous research should be done on the implications of the division into elements, aesthetically and structurally, as well as a study of stereotomies and effective methods of linking between elements, in a system thought from the whole and not as a simple form of post-rationalisation [7].

These pre-fabrication principles were applied by some laboratories and corporations that sought to quickly follow the evolution of technology. The Chinese company Winsun3D, for the creation of low-cost and fast-build housing solutions, has resorted to the pre-fabrication of large-scale components. For this purpose, they developed their own extrusion AM system for the production of structural components where, during the manufacturing process, they add metallic rebar to give structural strength to the concrete [8]. However, despite the development of the custom extrusion machine, so far, they have not yet extrapolated on the impact of technology on architectural forms, not drawing much of their potential.

Otherwise, there are projects that take advantage of discretization to explore the potential of AM. One of the most paradigmatic examples is Smart Slab, the prototype of a slab developed by ETH Zürich's Laboratory, Digital Building Technologies [9]. The slab design resulted from the structural optimization of the areas of greater and smaller load, introducing concave shapes in the latter and allowing to obtain a slab 70% lighter than if it were obtained by conventional methods, and more sustainable, since it uses less material. For the production of the lost formwork of the final prototype it was used a Binder Jetting technology (powder and a selectively deposited binder). The size of each of its 8 segments was limited by the printer workspace. After the formwork was obtained, it was filled with reinforced concrete with fibers, for later transport and assembly in the place through post tensioned connections.

Another interesting approach is the biomorphic-inspired column developed by the XtreeE for a school in Aix-en-Provence, France [11]. The 4 segments of the column formwork were manufactured trough customised concrete extruder supported by an industrial robotic arm. Then, the joining between parts by chemical glue and filling with high performance concrete resulted in a system that combines a complex geometric design with a high structural capacity.

6. Control of the manufacturing process

In addition to the size constraints referred to in the previous section, issues of strength and durability of materials, quality and manufacturing time are still major obstacles to the integration of these technologies in construction. In a field of experimentation that is still under development and is very focused on prototyping, it is essential the coordination between four factors: (1) environment, (2) material(s), (3) manufacturing process and (4) production time.

6.1. The production environment

The control over the manufacturing conditions has practical repercussions in the performance of the extrusion technique and also in the material behaviour at that specific context.

As far as the manufacturing site is concerned, there are two methods that have been adopted: the manufacture of components directly in the workplace (*in-situ*) and the production of components in a laboratory environment, followed by transportation and assembly at the construction site. Each method reveals its own conditioning factors.

Upscaling techniques based on continuous large-scale printing, referred to initially, naturally lead to in-situ manufacturing logics. This method forces the transportation of delicate and large-scale computer-controlled technology to the construction site, as proposed by the Contour Crafting Corp, or the Shamballa Technological Village project or the IAAC experiences with *"minibuilders"*. Although the potentiality of a single machine (or a machine system) is feasible and attractive, allowing to produce an entire architectural structure in a single run and minimizing the human workforce, the truth is that all the logistics needed for the machinery transportation and assembly or even on-site weather conditions are more difficult to control and potentially less productive.

In contrast, upscaling based on pre-fabrication processes in the laboratory, which is usually accompanied by discretization processes, allows greater control over the production conditions of the elements. However, this forces the transportation and assembly of parts on the job, increasing the need for post-production labor, resulting in the object constructed of an intelligent combination of the work of man and machine. Moreover, although the material extrusion methods, in principle, do not require closed-chamber printing like other AM technologies, in order to obtain high performances, control of the environment, techniques and production conditions is essential. The deposition process, with very high or very low temperatures, changes the behaviour of the materials and does not allow to strictly control the level of workability of the extruded pulp. Thus, laboratory production is not subject to variables such as meteorological/environmental conditions, for example, allows a greater dominance of the temperature and the whole manufacturing process and to explore optimal conditions for the deposition of the material.

6.2. The materials

Although in practical terms it is possible to exploit AM using materials already tested and commercialized, the research and adaptation of its properties should be considered. Factors such as plasticity, flexibility, hydration, texture or the paste own friction have a direct influence on the extrusion process.

In addition to the reaction and resistance of the materials during the deposition process, it is essential to realize their behaviuor after printing – the time and temperature of the curing and firing for the ceramic, the study of the transition process from liquid to solid in concrete or temperature and heating and cooling time for polymers, etc. – are important issues regarding rigorous 1/1 scale results.

Diverse stakeholders on this field of research, realizing these needs, paved the way for the exploration of new materials and composite materials that result from the addition fibers to improve the structural strength, or superplasticizers to control viscosity maintaining the moisture content of the mixture, etc..

Each experiment represents an evolution of the raw materials. CyBe Industries, a company focused in AM in concrete, has developed an optimized mortar, which acquires consistency in a few minutes achieving structural strength in just one hour, dramatically reducing the time of construction [12]. Also the XtreeE, together with the cement manufacturer LafargeHolcim, developed a series of concrete mixtures specifically adapted to 3D printing. From another point of view, the WASP printer manufacturer, in the Shamballa Technological Village project, has successfully tested the exclusive use of local, environmentally friendly inerts based on a mixture of soil, straw and water.

Lastly, on the context of ACLab, a study on the properties of ceramic paste was conducted in order to improve its extrusion behaviour and ensure a good performance during the dehydration process. A set of tests were conducted using the Pfefferkorn method to infer an optimal relation between the paste hydration and viscosity [14]. The firing process was also analyzed, different temperature curves were revealed different levels resistance and shrinkage. In addition, experiments of composite materials of stoneware paste and small percentages of powdered cellulose resulted in an interesting reduction of cracks after the curing and firing processes and decrease of the pieces final weight [15].

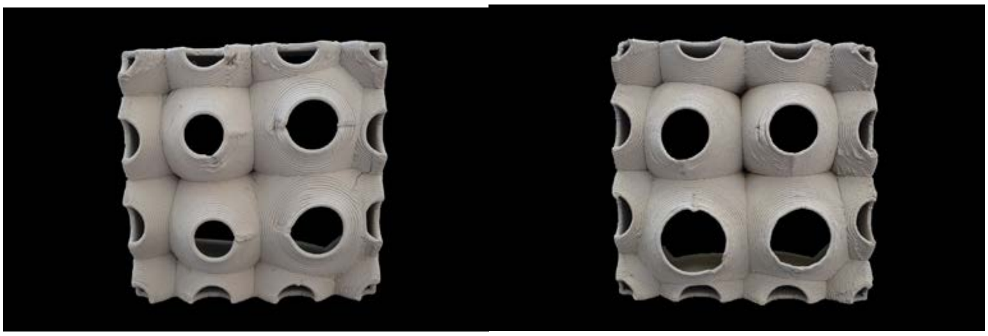

Figure 4: Same block produced with stoneware paste (left) and a mix of stoneware paste and cellulose (right).

6.3. The process

In addition to material studies, information on machine operation and extrusion processes – such as air pressure, extrusion flow, speed and kinematics of the printer, the nozzle diameter and their relation with the number of layers and thickness, inclinations and radii of curvature of the fabricated geometries, etc. – should be considered and integrated in the design, being adapted to each case [16].

Although many of these parameters are essential to control the extrusion process they represent constraints that are not always transposable to the digital model or their effect is not predictable for some models. In this paper we analyze two of the major issues: geometric constraints (during the printing process) and deformations in the manufactured object.

6.3.1. Geometric constraints

One of the most limiting factors in the processes of AM by extrusion is the production of inclined surfaces. If, with the polymeric extrusion, one can easily obtain inclinations of 60° without the need for additional supports, in the case of the LDM technique such values cannot be obtained.

As a reference for the reduced scale, in the context of AM in ceramic paste, a set of sequential tests were carried out in the ACLab [14] revealed that inclinations with angles greater than 30° resulted either in noticeable deformations or in the abatement of the surfaces. From another point of view, there are two methods already developed to exponentiate these values: (1) controlling the movement of the printer head or (2) using auxiliary structures.

The former is deeply connected with the control of the movement of the extruder tip. The XtreeE proposed a system that, according to their own, improves the AM process on a large scale. By using a 6-axis robot, instead of the deposition following a constant layer height and a vertical extrusion, it is performed tangentially to the inclination of the object and with height variation between layers, achieving a larger and more uniform area of contact between layers [17]. A similar system is possible using a 3-axis printer. Although not being able of rotating the extruder nozzle, height variations between layers can be customised in order to increase the adhesion between the layers and, of course, to allow greater inclinations and superior strength.

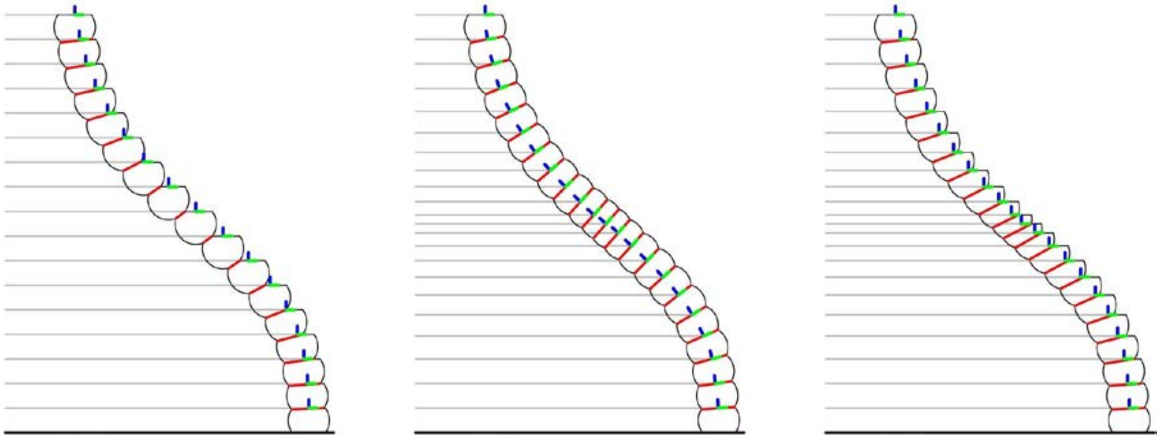

Figure 5: Schematic cut using the vertical extrusion system with equal height between layers (left), tangential continuity method proposed by XtreeE (center) and vertical extrusion system with variation of height between layers appropriate for any 3-axis machines (right).

Other method is concerned with the creation of support structures. When the top layer exceeds the contours of the former making the structure unstable, it is very common in FFF to use a thinner structure or a soluble material in order to allow a continuous deposition of the material and its removal in post-production. LDM is substantially different as the material continues to react during and after the extrusion process. Some tests were performed in the ACLab considering reduction of the area of contact between the desired model and the supporting structure to the minimum necessary, namely by printing the support structure in a direction opposite to the direction of the part produced, it became possible to create protrusions or the ceramic deposition at an angle of 45°, being conceivable in the curing/firing phase to separate the models.

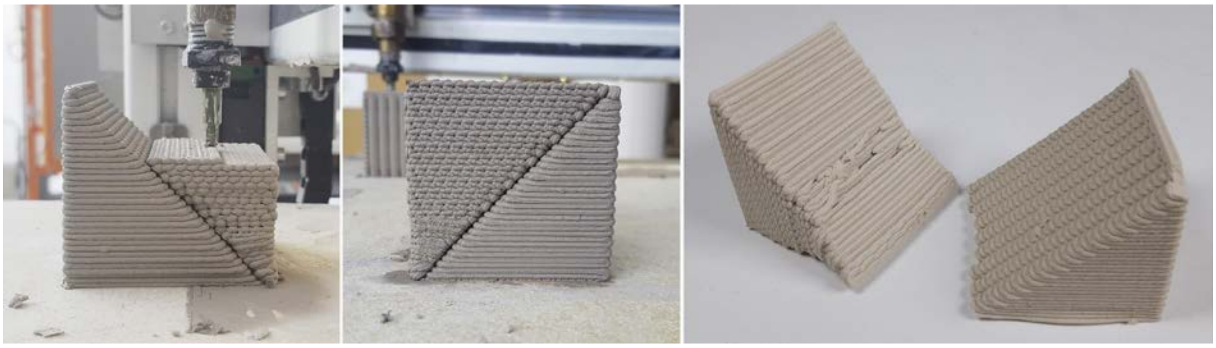

Figure 6: Ceramic deposition on support structure - Printing process (left, center) and after firing (right).

Another supported extrusion solution is presented by Amalgamma, a group of master's students from the Bartlett School of Architecture. This method looks for references in the powder impression and combines it with the concrete extrusion process. Thus, while the concrete is extruded on a platform, layer-by-layer, a bed of granular material that supports the following layers, is deposited, making possible the printing of objects with various suspended parts [18].

6.3.2. Geometric deformations

Although AM by extrusion is able of producing objects with margin of error of tenths of a millimeter, it is practically impossible to produce objects with exactly the same shape and physical characteristics.

The printed object, although similar to the computational model, is always subject to deformation, both during the manufacturing phase and the curing or drying phase.

The shrinkage due to the dehydration of the material is perhaps the main cause of geometric changes, mainly in ceramic materials, whose loss of volume of the printed objects difficult the agreement between the scales of the digital and physical models. In addition, the shrinkage effect is not uniform. During the drying or firing process, the object is subjected to a set of forces (friction caused by the base plate, its own weight, etc.) that directly influence its final geometry, further distancing the physical model of the digital model. As an example, the Ficus Column prototype developed in the ACLab at 1/5 scale, had a mean shrinkage of 21% in height, 7% in the base and 15% in the top (Figure 7). In this case, after being analysed, these data allowed to generate compensations in the digital model making it possible to create links between the printed elements.

However, these parameters are deeply dependent on the scale of printing. Recent tests carried out at 1/2 scale allow to foresee a whole new associated problem. For constraints related to the limits of the printer's work area, to increase the scale, it was necessary to subdivide the column into more parts which caused the ribs to be undone (the geometry does not stay connected at the top and bottom). This circumstance, together with the reaction of the material during dehydration caused the abatement of the ribs and the subsequent rotation of the upper connecting surfaces made it difficult to articulate with the other parts. A solution to avoid these constraints is shown in the previously mentioned biomorphic inspiration column for Aix-en-Provence. In it, XtreeE solved this problem through the joint printing of an auxiliary structure which limits their degree of freedom and increases the resistance of the whole, namely, to resist the deposition of concrete. Afterwards this auxiliary geometry had to be cut off after being assured that the structure is self-supporting.

Figure 7: Ficus column system manufactured in ACLab at 1/5 and 1/2 scale

6.4. Manufacturing time

Manufacturing time is an essential factor to realize the potential of AM at the construction scale, but its control is essential to enable parts with high levels of quality. A balance between the speed of manufacture and the extruder path must be sought in LDM technique. Increasing the scale of the object is usually associated with an increase in the thickness of the layer, change in the section of the extruder tip or even increase the speed of movement. These are controllable parameters that alter the resolution of the produced models, as such, must be tested according to the desired geometry and finishing. In addition, very high layer heights, sharp radii of curvature are likely to generate conflicts with the kinematics of the machinery, which can, by excessive vibration, generate unstable structures and, in the limit, lead to the collapse of the fabricated part.

The solution to accelerate the process should not fall into processes that increase the fragility of the object obtained, but often only increase the number of printers working simultaneously. For example, at Trabeculae Pavilion, Roberto Naboni in collaboration with WASP used a 3D printer’s farm installed in the laboratories of ABC's Department of Politecnico di Milano, consisting of 5 Delta-type printers working continuously for 4352 hours to produce the 352 components that conform the pavilion [13]. In this sense, the printing process must be optimized but it should not force the limits of technology, nor reduce the quality of the part produced.

7. Conclusions

AM techniques are an asset to traditional building systems. Its application allows to obtain more sustainable solutions and a greater freedom of design - manufacture of non-standard elements, addition of multifunctional properties, autonomous construction systems, more rigorous forecasting of delivery times, etc. However, its application still has many obstacles that need to be overcome.

The issues discussed throughout the paper outline the potentialities and constraints of the adequacy of AM systems on real-scale. It was tried, with a wide set of examples, to discuss topics that directly or indirectly have repercussions in the solutions of project and the results obtained. To this end, questions were raised regarding the manufacturing scale and quality control of the manufacturing, building on the different approaches, possible methodologies for the adequacy of these rapid prototyping systems, to the needs revealed by an increase of scale. In each project/experience there is a meaningful learning.

Regarding the size of the manufacturing, solutions were considered that deal with the suitability of the machine to the scale of production or suitability of the different components of this machine to the size of the machine. In terms of quality control, a number of variables have been addressed that affect extrusion methods. In this sense, issues related to the production environment, materials, suitability of the extrusion process and manufacturing time are essential to obtain unique results.

These results are deeply dependent on the scale of manufacture. Thus, the production of reduced-scale prototypes can help dispel doubts about suitable functional or extrusion techniques, but should not negate the occurrence of full-scale tests where the behaviour of the materials, the extrusion system, and the manufacturing will be differentiated.

In addition to the research and development on the AM technologies by extrusion, which this article focuses on, it is essential that these be adapted to project development. The production of components should not be an issue at the end of the process, but should be put in place from the outset. In this sense, the manufacturing constraints, recognized by experimentation, must be integrated in the computational models from the design phase, in order not to require changes that are crucial for their manufacture.

Some of the prototypes referred revealed viable solutions, but there are still additional improvements in terms of speed and cost associated with higher performances. There is a wide field of research to explore until the AM is able to respond adequately to all the needs of the construction industry.

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