

# Initial Developments and Projections of 3D Construction Printing

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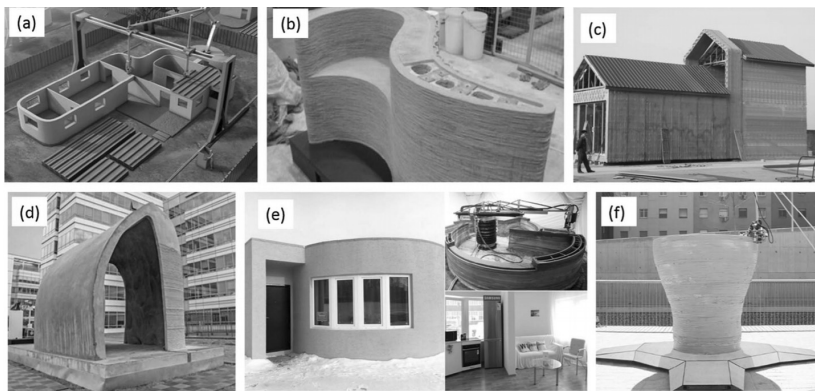
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**ABSTRACT:** 3D Construction Printing is a novel technology to elaborate building parts by material deposition. This technique is emerging through several university and entrepreneurial initiatives, mostly in developed countries. Some exploratory buildings and/or pieces have been created and diverse companies plan to execute large constructions. This article aims to review architectural and urban projections of this technology based on these experiences and initial tests and developments in Concepción, Chile. Supplies and equipment has been collected and a number of concrete printing trials has been carried out. Additionally, parametric programming of 3D-printed walls is being developed in a BIM platform in order to generate and evaluate architectural models. Also, a robotic installation is being set-up with the support of a national program on building productivity, research centers and industrial companies. The material tests have demonstrated the feasibility of construction printing with local materials, in addition to an important reduction in the time and resources needed to produce pieces with different shapes, although this process does require automation, structural verification and large-scale execution. The parametric programming in BIM shows the integration of the design-to-construction process, in addition to versatility and optimization of architectural designs. The planning of an industrial installation expresses the convergence of different stakeholders in this technology and a particular interest in to develop local supplies and machines. These activities and other experiences suggest the impact of 3D construction printing on the emergence of new manufacturing systems for buildings, that impels an architecture of curved profiles and appealing spaces that can become part of the real-estate market as experimental neighborhoods and/or iconic buildings, related to new social trends.

**KEYWORDS:** 3D Construction Printing, Digital Fabrication, Parametric Design, Building Technology.

## INTRODUCTION

Several initiatives around the world, usually in industrialized nations, are testing the digitally-controlled three-dimensional deposition of fast solidifying fluid material to produce building parts (Fig.1), which has been called "3D Construction Printing" (Perkins and Skitmore 2015; Labonotte et al 2016; Wei et al 2017, Panda et al 2018). In most of these experiences, cementitious mixtures are expelled from a nozzle hung from gantries or robotic arms to apply successive layers as additive manufacturing without formwork (Bos et al 2016, Duballet et al 2017). Certain initiatives have managed to execute small buildings, and some companies have promised to build large constructions, with shorter terms and lower costs than conventional processes (Perkins and Skitmore 2015; Labonotte et al 2016). Although equipment, materials and benefits are still being tested, it has been asserted that this technology will transform the construction industry, architectural design and the building of cities (Hager et al, 2016). This research aims to discuss the projections of 3D construction printing in architecture and towns, based on these experiences and initial developments of this technology in Chile. It includes tests of the mechanical deposition of cementitious compounds, parametric programming of architectural designs in BIM systems, and the preparation of a robotic installation.



**Figure 1:** Experimental works created with 3D construction printing around the world: (a) USA, (b) UK, (c) China, (d) France, (e) Russia, (f) Spain. Source: (Panda et al 2018)

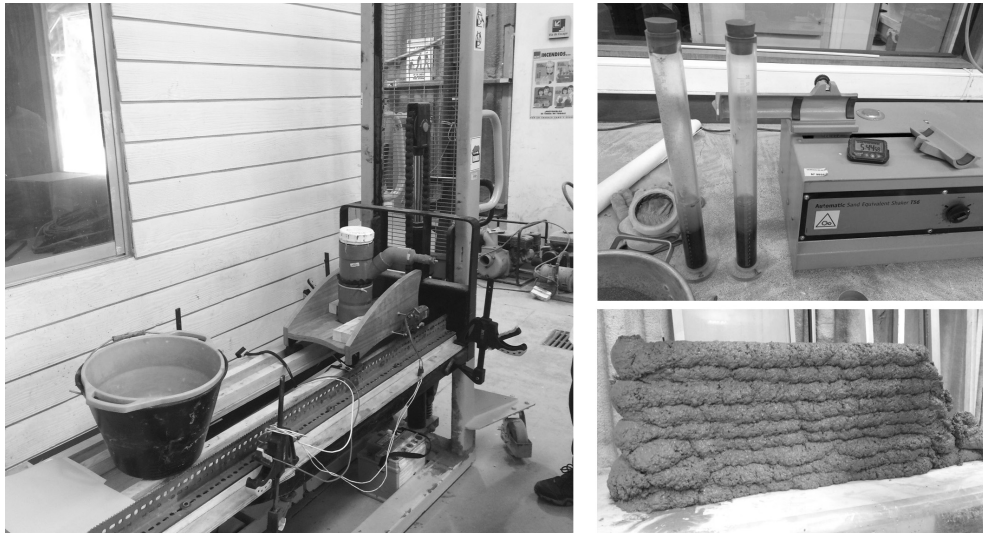
## 1.0 INITIAL DEVELOPMENTS IN CHILE

### 1.1. Tests of 3D-Deposition of Cementitious Composites

To review the elaboration of building elements through the three-dimensional deposition of cementitious compounds available from local industries, first a mechanical system was developed. Subsequently, diverse supplies were collected to make mixtures, basic trials were conducted, and several concrete machines were used. The tests focused on determining composites with the proper fluidity and early solidification required to lay down a horizontal cord by vertical extrusion in motion, and sufficiently fast hardening to support the next cord in a short period of time and maintain the stability of the sequence (like Malaeb, 2015; Torres, 2016, and Bos et al, 2016). Different mixing and pumping machines has been also tested, as well as the preparation of nozzles, clamping and control, for a large automated installation.

A load elevator, which provided adjustable vertical displacement, is used as the base of the test system, together with a small trolley mounted on rails, with a 1/8 HP electric motor for horizontal displacement, and hydraulic pistons with lateral axes to achieve rotation (with fixed support). The deposition system is made of a 60cm long, 110 mm diameter PVC tube that ended in a reduced 45 mm diameter, with a valve for air intake under pressure from a 2 HP compressor (Fig. 2). In addition, a mechanical mixer and integrated controls for the motors are used to synchronize operation. The tube is filled with the prepared mixture (approximately 5 liters), then the compressor and motor are turned on simultaneously to deposit a cord approximately 8 cm wide and 5 cm high, in a one-meter-long horizontal movement. After each horizontal deposition, the tube must be reloaded, the trolley moved to the initial position and the motor restarted for the following cord, which can be executed in a curve with lateral pistons. In the initials tests, the prepared mixtures were reviewed, and times, speed of deposition, hardening, and dimensions of the results executed were measured.

In the tests, different combinations of aggregates, cement, water and additives were used, in addition to compounds prepared. Currently, tests are also being carried out with micro-aggregates and sieving to achieve proper rheology and review fiber aggregates. Furthermore, standardized tests of viscosity, creep, compression and resistance are being conducted on the compounds, and normalizing a measurement of deposition by video recording, sizing and hardening by Vicat needle. Deposition is also being tested with another set of equipment in which mixtures are projected through a hose using pressurized air (shotcrete), while the nozzle is supported by rails.



**Figure 2:** Left: equipment to test material deposition; Upper-right: evaluation of sands; Lower-right: sample of material deposition. Source: (Author 2018)

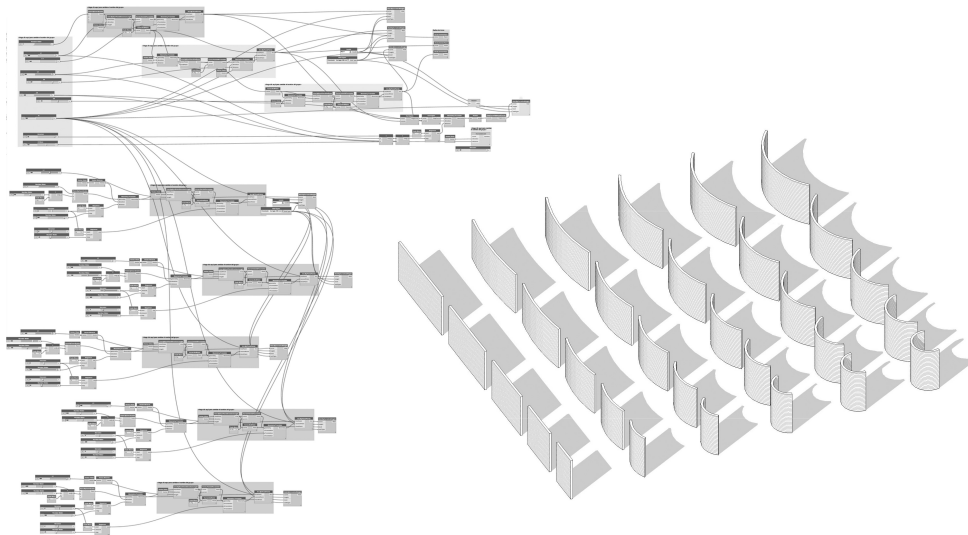
### 1.2. Parametric Design of Walls with 3D Construction Printing

In order to plan the architectural composition of walls created with 3D construction printing, a parametric programming is being developed in a BIM platform (with Dynamo language in Revit), based on similar works in the field (Raspall, 2015; Kasperzyk et al, 2017; Craveiro et al, 2017; Sacks et al, 2004; Davtalab et al, 2018). The programming assumes a machine-work space of 10 x 3 meters and 3 meters in height, with a capacity for three-dimensional deposition of self-supporting reinforced cementitious mixtures of 10 to 40 cm. in thickness. Thickness may be smaller depending on the curve, height and lateral support required to maintain

structural stability. This can be reviewed by exporting the model to a finite element software, with point loads and minimal deformation. This production capacity is achievable both with the planned installation of a robotic arm with an automated rail and with mechanical equipment with rails for three-dimensional displacement of concrete delivery hoses. That is, it is estimated that this type of wall can be executed on site using specific equipment at lower costs than robots. Based on the workspaces to execute the walls, the architectural project is divided into magnitudes equivalent to or smaller than the workspaces, to establish the consecutive locations of the machinery. This operative subdivision also makes it possible to plan the equipment installation sequence according to the progress of execution to ensure clear transportation routes. If necessary, some modules or openings are postponed, in order to remove equipment when closing walls.

In the parametric programming, the main sizes of the configuration must be indicated at the beginning. Therefore, a linear or rectangular arrangement can be initially chosen, which can be applied consecutively in the same horizontal plane or successive vertical levels for larger configurations. The subdivision of parts is then carried out according to the maximum dimensions of operation (with splice margins). Options make it possible to ensure the regularity of parts of the greatest possible length, or a combination of sections, as well as to develop stretches that match at the corners. Afterwards, the sections are traced with random curvatures or those defined by the designer, in a similar way in all the sections or randomly within ranges, and on the same side or sequentially on opposite sides (which gives greater stability, but reduces the internal area). The criterion of structural optimization defines thicknesses according to height, curvatures and continuity, thus establishing parametric families of walls in the BIM environment (Fig.3). Random generation can develop a number of sequentially named alternative BIM models, thereby giving the designer different configuration possibilities.

The various models generated in the BIM environment can be quantified, thereby obtaining the total material required, according to the amount, length and thickness of walls. The number of sections can also be determined, as well as the total length of sections, which in turn can be used to calculate the total operating time (multiplied by the number of cords in height and speed of execution, plus the machine's transfer time). Then, models can then be compared in terms of material or processing costs, which are normally different depending on the curvatures, in addition to their spatial configurations, from interior or exterior perspectives. The process can also be planned based on steps, according to work schedules, by defining the work route and machinery installation positions, and anticipating the requirements involved. Likewise, this plan can be integrated with the rest of the BIM model to combine with other elements, such as floors or covers (which can also be executed with construction printing), including doors, windows, services, and terminations, among others. Furthermore, climate, structural, or infrastructure management can be incorporated into analyses. The programming developed is currently being completed with the ability to generate variable height configurations and combined splices to ensure continuity, parallel, cross-linked or embedded layouts for structural performance and material reduction or combination with different performance requirements (i.e. resistance, thermic, acoustic, chromatic). Finally, the model generated is exported with the elements of parametric families, in solid production (STL) and/or the format for machine control (KRL).



**Figure 3:** Parametric programming and examples of walls generated. Source: (DGNL Studio 2018)

### 1.3. The Implementation of a Robotic System for 3D Construction Printing

To boost the productivity and sustainability of construction, the Chilean government established a national development strategy (Corfo, 2014; Gutierrez, 2016) that included the creation of technology centers adjudicated by a consortium of local universities, with public financing and private collaboration. At the Universidad del Bío-Bío, located in Concepción, the main city in the south of Chile, which is characterized by its regional services and forestry resources, a large workshop is planned. This facility is targeted to elaborate prototypes in two areas of development: elements made of concrete, the primary construction material in the country; and prefabricated components made of wood, a material with environmental quality and local production. Both areas will be related through a mounting crane and integrated with a robotic system.

In order to experience 3D construction with concretes, polymers and/or biomaterials, the installation of an industrial robotic arm (Kuka KR120R2500) on a 10-meter rail with a concrete pump for a 120-liter pond with a 30 meter hose was approved through additional state funding. This installation will have a 140 m<sup>3</sup> workspace (Fig. 5) in which the arm and pump nozzle are able to make continuous walls of up to 15 meters in length and 3 meters in height, with six degrees of freedom. This will be the first 3D construction printing installation in the country and the most versatile and largest in Latin America. It will be managed by Universidad del Bío-Bío with the support of Universidad Santa María de Valparaíso; as well as the Research Center for Advanced Polymers and the Center for Nanotechnology and Bio-materials of Concepción; the PRODINTEC Foundation of Spain, which has been conducting research in 3D construction printing for five years; and Cementos Bío-Bío, Ready Mix and Bottai, the largest companies in the country devoted to cement production, concrete manufacturing and prefabrication, respectively. Financing has also been approved for additional research with a small-scale installation of robots with cars and 3D plastic filament printers that reproduce construction printing processes to experiment with multi-robot coordination in the execution of buildings.

## 2.0. PRELIMINARY RESULTS

### 2.1. Preparation and Samples of 3D-Deposition

To date, the equipment to test 3D-deposition has been used to carry out partial and complete elements, as well as review different compounds, machineries and procedures. In the test facility, 18 deposition samples have been completed with supplies available on the local market. The first twelve produced continuous cords, and the following six resulted in overlapping cords. In addition, other partial tests conducted with different mixtures were not able to produce continuous cords or regular finishing. In this way, the compound that was able to achieve adequate flow and early hardening was determined to be a mix for quick concrete called "Topex". In the first samples completed, adjustments were made in the configuration of the equipment in terms of operational control, working speeds, video recording and measurements. The average horizontal deposition speed of the initial samples was 22 seconds/meter, for cords 10 to 15 cm. wide and 4 cm. high. With additional time of around two minutes to load and reposition the trolley and by mixing in parallel, a production speed of 0.4 meter/min was obtained. Small linear and curved walls of up to 9 cords in height were formed, during a total production time of 24 minutes, with 3 minutes of deposition, which corresponds to an execution speed of 0.8 m<sup>2</sup>/hour. Hence, a two-meter high wall could be made in 2.5 hours per meter of length, or in a more continuous process, without intermediate tasks, in 20 minutes per meter. This means that a wall of several meters can be completed in a few hours. Although production speed has not yet been verified for large pieces, it should be similar to other experiences reported (Malaeb et al, 2015; Torres, 2016; Ma and Wang, 2017), and is reduced in comparison with the various days required for the traditional execution of a similar wall, which involves formwork, reinforcement, pouring, curing, removing formwork, and repair of failures. Also, conventional construction of these elements entails more materials, personnel, accidents, quality control, administration, waste, transport and environmental impact.

Additionally, different inputs, mixers and pressure pumps has been tested. Therefore, mixtures with improved rheology (regular distribution of particle sizes of materials) were prepared to get pasty compounds. Seven samples of fine aggregate from local producers were collected, sieved and combined with cements and accelerators to develop preliminary tests. The expulsion nozzle was mounted on a longer-range horizontal rail (2 meters), with a larger capacity motor, and the vertical lift and transverse displacement system was designed to achieve a working space for samples up to 1.8 meters long and 1.2 meters high. In the future, these capacities must be industrialized, by means of mechanical or automated equipment, regular supplies and specialized staff. However, these experiences demonstrate the initial feasibility of creating building elements through construction printing with products available in the country, and their adaptability to different circumstances or local conditions, resulting in a significant reduction in time and resources in relation to conventional construction.

## 2.2. Generation and Assessment of Parametric Models

The programming developed to generate models of walls according to 3D construction printing features made it possible to implement a procedure for the design and evaluation of architectural alternatives in a BIM environment. A number of production assumptions are taken into consideration and used in a planning method with computational support to determine more effective and meaningful compositions. The design process is then integrated in a BIM platform, with parametric families of building elements determined by specific construction printing equipment, and the capability to generate and assess models, as well as to export information for analysis, quantification and visualization, and later, plan the execution and control of the machinery (such as Davtalab et al, 2018).

A building framework is first established by proposing a sequence of work spaces with fitting ranges to ensure continuity of production, in addition to equipment operating conditions such as thickness, deposition speed, and the resistance capacity of the material, among others. With these properties, geometric rules are programmed by means of graphic components and relationships through Dynamo in Revit software, with some instructions in Python to determine conditional recursive sequences and families of walls. The procedure then generates a set of models and also a schedule of quantities that can be exported. Furthermore, a macro is created in Excel to examine the data extracted in the analysis of models.

After several preliminary tests with different generation values, the programming was tested with an exercise to create an enclosure of 20 x 40 meters, with wall segments of a maximum of 10 meters, which may have a regular curvature, like an arc. It assumes that curvature implies different structural capacities (Martens et al, 2018), and therefore diverse thicknesses in different wall families. The programming makes it possible to develop 30 simultaneous models with different amounts of wall segments and curvatures (Fig. 4). Each model is assigned a code of variables, and subsequently elements are tabulated and exported to the spreadsheet. Thus, models are used to quantify the project, considering the total length proportional to the execution times, and the volume of material equivalent to the cost. Then the fastest and the cheapest models are identified and also the appropriate combination of both. From these three models, interior and exterior views are generated. In this way, the models are quantitatively and qualitatively evaluated. The process must be validated with the operational capabilities of the equipment, as well as in actual design activities. However, it facilitates the systematization of the design and execution processes with construction printing through digital integration targeted at developing the versatility and optimization of the building.

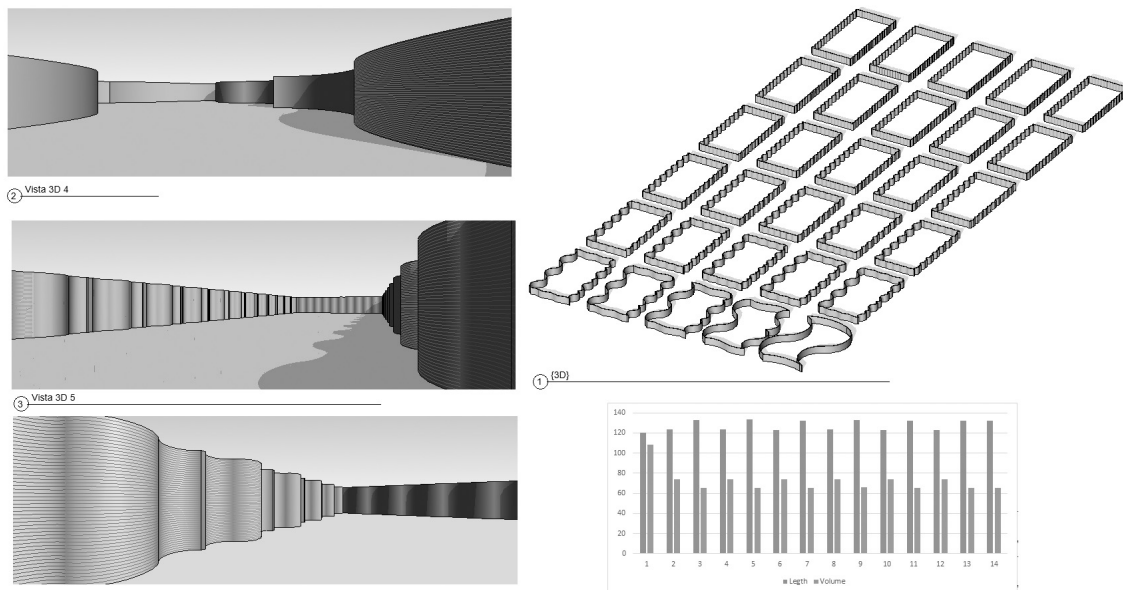


Figure 4: Models generated, visualizations and quantitative assessments. Source: (DGNL Studio 2018)

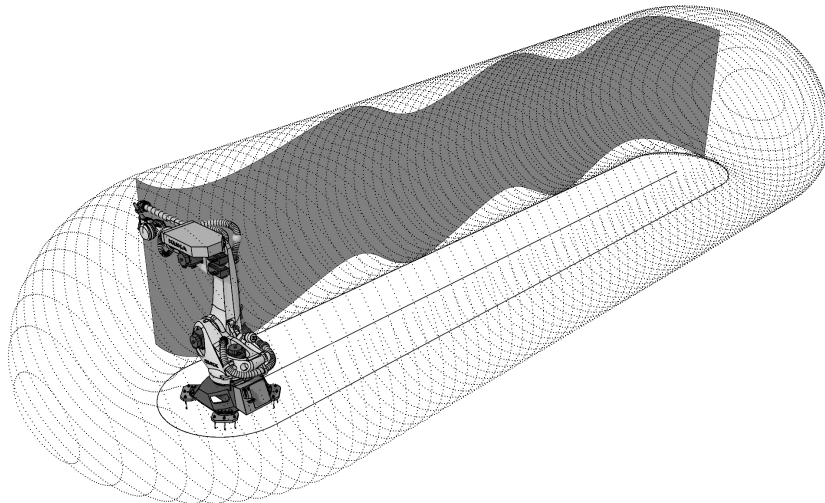
## 2.3. Agreements on and Plans for a Large-scale Robotic Installation

State, industrial and academic stakeholders have converged in a plan to install a large-scale robotic system for construction printing in Chile in order to move towards more efficient building with less environmental impact (Bogue 2018). The provision of state funds oriented towards the productive and sustainable development of the country; university interests in professional training with a perspective on the future; and the motivation of private companies aimed at maintaining or increasing their participation in the construction

market, express trends that come together in the planned installation and which have been consolidated through financing approval and specific work agreements.

A technical board has been formed with representatives from the participating institutions and companies, collaborative developments have been prospected and joint tests are being carried out. Cement companies have provided concrete injection equipment and various materials to conduct pumping tests. The Research Center for Advanced Polymers has supplied samples of polymer blends and injected polyurethane to test printed elements. The Center for Bio-materials and Nanotechnology is preparing cementitious compounds with nanocellulose fibers for testing, to develop local products with low environmental impact, and better resistance and thermal performance for construction.

The agreed installation expresses a joint development perspective in the building sector. It involves the production of cementitious mixtures for deposition in: a plant for prefabricated elements, the site-work for the execution of the main parts of buildings, as well as the manufacturing of products and equipment, and large-scale construction in medium and larger dimensions, with the participation of local companies, state programs and national standardization. It also represents a motivation to promote new compounds with polymer blends and bio-materials, in search of lower execution costs and greater constructive and environmental functions. The agreements and plans developed should materialize in the installation and joint experimentation, with the adequate provision of resources and coordination of activities. They are evidence of the relevance of this technological innovation and its potential to have a productive impact on the local construction industry and to link stakeholders and society.



**Figure 5:** Working space of the installation. Source: (DGNL Studio 2018)

### **3.0 ARCHITECTURAL AND URBAN PROJECTIONS**

#### **3.1. Architectural Compositions**

According to the experiences detailed previously and reports of diverse initiatives around the world (Perkins and Skitmore 2015; Labonotte et al 2016; Wei et al 2017, Panda et al 2018), the developments in 3D construction printing have mainly focused on the main vertical elements of buildings. Some cases have involved inclined or vaulted coverings, or prefabricated pieces or sections that are later moved and mounted on the ground (Yuan et al, 2018). The vertical printed elements are self-supporting planes and diverse in form, usually with rounded corners and/or curved parts; so that the first printed constructions have mostly been horizontal buildings, low in height with sinuous shapes, and integrated with conventional products for roofing, fenestration, services and/or terminations. There is great interest in increasing the insulation, finishing and resistance of these vertical compounds, as well as in curved fabrication, which together provide more stability, better performance and novel spatial experiences and meanings associated with new technologies, environmental requirements and/or cultural attributes. Most stakeholders and entrepreneurs of 3D construction printing are motivated to develop large-scale housing projects with short construction terms and innovative features, but it is also possible to construct buildings for commercial exhibition use, industrial workshop or public services. Due to the incipient conditions of 3D-printing technology, which depends on new

and large equipment, in addition to unique supplies and specialized personnel, the buildings could be concentrated in new urban complexes promoted by local developers.

### **3.2. Building Processes**

The planning and design of buildings with 3D construction printing should integrate this technology early on in the process, thereby taking advantage of its technical and expressive features (Delgado et al, 2018). The available local suppliers must be taken into consideration, together with the formal, constructive and economic condition of the architectural configuration. Previous experiences should be used to determine the specific attributes of the buildings, while also testing some parts or characteristics that have not previously been developed. Hence, traditional design documents, construction management and experienced personnel must be combined to progressively integrate these new technical capabilities. The digital management of the process should motivate an increasing exchange of documents, and agreement on formats, tasks, protocols and analysis potential, especially related to visualization, planning, structural, environmental and/or economic features. This implies the need to normalize and regulate some constructive conditions, systems and commercial products in relation to the scope of elements and buildings that can possibly be executed, for example in functional properties, articulated with their commercial and social projections. Development will most likely concentrate on specific products (buildings, elements or applications), which call for commercial and constructive advantages, in sufficient magnitudes and with a permanent demand to sustain them. This can impel productive synergies, or perhaps also financial bubbles, which will enable new close linkage between the market, society and the construction industry, along with flexible and intense professional developments with promising capabilities.

### **3.3. Urban Perspectives**

3D construction printing has been promoted to reduce work time and resources, which was confirmed in the first experiences with deposition and digital integration capabilities, although they do require industrial development. These conditions are crucial in construction due to the large costs and duration of planning and execution that involve previous expenses in materials and personnel with late exploitation, and require high amounts of financing and management efforts. Consequently, decreases in time and resources should result in lower costs and enable the participation of smaller companies and stakeholders than in conventional construction. However, initial actions depend on advanced capabilities and equipment, which require greater technical and financial support, waiting for dispersion through entrepreneurship. It should also be considered that the lower costs of printed construction should be linked to lower value lots, usually located in the peripheries of cities, which may be close to production sites, thus encouraging experimental neighborhoods or exceptional buildings in these sectors. The versatility of technology and digital processes enables local adaptation that must be oriented towards the relevance and effectiveness of buildings and reducing social and economic gaps. In the long term, the development of 3D construction printing should motivate real estate decompression, the acceleration of the industry and social initiatives, and connection with new cultural trends and environmental commitments, thereby promoting the achievement of a collective well-being.

## **CONCLUSIONS**

This work presents initial works with 3D construction printing in Chile to explore its architectural and urban possibilities. The results of material tests, design programming and the planning of a large installation demonstrate local feasibility, architectural features and sectorial interests related in particular with biomaterials and large-scale construction, which would enable the production of singular buildings and urban complexes. Like also others initiatives around the world are showing. Nevertheless, there are also important challenges in the development and industrialization of this technology. These experiences demonstrate the capability for fast execution and process integration, and the potentialities of curved patterns, performance and novel constructions based on natural resources and infrastructure needs. This technology can promote projects for new city sectors and exemplary buildings associated with commercial, environmental and/or cultural motivations. Through experimentation in developing countries such as Chile, local adaptations and specific initiatives can be achieved that complement the global emergence of this technology, thus establishing a more varied horizon of architectural and urban evolution.

## **ACKNOWLEDGEMENTS**

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## **REFERENCES**

- Bos F., Wolfs R., Ahmed Z., and Salet T. 2016. *Additive manufacturing of concrete in construction: potentials and challenges of 3D concrete printing*, Virtual and Physical Prototyping 11:3, 209-225
- Bogue R 2018 *What are the prospects for robots in the construction industry?* Industrial Robot: An International Journal 45/1 1-6

Corfo, 2014; *Estrategia Nacional de Productividad y Construcción Sustentable*, Santiago de Chile: Corporación de Fomento de la Producción.

Craveiro F., Bartolo H.M., Galec A., Duarte J.P., Bartolo P.J. 2017, *A design tool for resource-efficient fabrication of 3d-graded structural building components using additive manufacturing*. Elsevier: Automation in Construction, Vol. 82, 75-83

Davtalab O, Kazemian A, Khoshnevis B 2018, *Perspectives on BIM-integrated software platform for robotic construction through Contour Crafting*, Aut. In Construction 89, 13-23

Delgado D, Clayton P, O'Brien W., Seepersad C., Juenger M, Ferron R. Salamone S. 2018 *Applications of additive manufacturing in the construction industry – A forward-looking review*, Aut. In Const. 89, 110-119

Duballet, Baverel O., and J. Dirrenberger J., 2017, *Classification of building systems for concrete 3D printing* Elsevier: Automation in Construction 83, 247–258

Gutierrez, A. 2017, *Hoja de Ruta PYCS 2025*, Santiago de Chile: Corporación de Fomento de la Producción.

Kasperzyk C., Kimb M-K and Brilakisa I. 2017, *Automated re-prefabrication system for buildings using robotics*, Elsevier: Automation in Construction, Vol. 83, 184-195

Labonnote, N., Rønquist A., Manum B. and Rüter P. 2016. *Additive construction: State-of-the-art, challenges and opportunities*. Elsevier: Automation in Construction 72, 347–366

Ma G. Wang L. 2017 *A critical review of preparation design and workability measurement of concrete material for largescale 3D printing*, Front. Struct. Civ. Eng. Springer-Verlag DOI 10.1007/s11709-017-0430-x

Malaeb Z., Hachem H., Tourbah A., Maalouf T., El Zarwi N. and Hamzeh F. 2015, *3D Concrete Printing: Machine and Mix Design*, International Journal of Civil Engineering and Technology, Vol. 6, Iss. 6, 14-22.

Martens P Mathot M, Bos F, Coenders J. 2018 *Optimising 3D Printed Concrete Structures Using Topology Optimisation*, in D.A. Hordijk and M. Luković (eds.), High Tech Concrete: Where Technology and Engineering Meet, DOI 10.1007/978-3-319-59471-2\_3

Perkins I. and Skitmore M., 2015, *Three-dimensional printing in the construction industry: A review*, International Journal of Construction Management Vol. 15, Iss. 1.

Panda B., Paul S., Mohamed N., Tay D. 2018, *Measurement of tensile bond strength of 3D printed geopolymers mortar*, Elsevier: Measurement Vol. 113, 108-116

Raspall F., 2015, *A procedural framework for design to fabrication*, Elsevier: Automation in Construction, Vol. 51, 132-139

Sacks R., Eastman C., Lee G., 2004, *Parametric 3D modeling in building construction with examples from precast concrete*, Elsevier: Automation in Construction, Vol. 13, Iss. 3, 291-312

Tay Y-W., Panda B., Paul SC, Noor Mohamed, Tan MJ., Leong KF. 2017. *3D printing trends in building and construction industry: a review*, Taylor & Francis: Virtual and Physical Prototyping Vol. 12, Iss. 3

Torres R., 2016, *Diseño de hormigón para impresión en 3D*, Universidad Politécnica de Valencia: Master Thesis.

Yuan Z, Sun C, Wang Y, 2018 *Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings*, Aut. In Construction, 88, 13-22