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Development of Variable Residential Buildings with 3D-Printed Walls

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Abstract: New 3D-printing technologies allows to make constructive elements, especially walls, faster and with formal diversity. The 3D-printed elements usually have self-supporting capacities, but they need to be reinforced or integrated into larger structures, to make buildings of large extension or height of several floors. This work proposes a residential construction strategy, focused on Chile, which combines a modular main reinforced concrete structure with partitions made of 3D-printed walls to obtain different housing organizations. For this, a structural grid and range of volumes are defined in BIM. In addition, a parametric programming is developed and prototypes of 3D-printed walls are made. The volumetric development provides a wide repertoire of residential surfaces, while the main structure provides a great flexibility of occupancy. The programming organizes the design and execution process, with numeric analysis and visualization capabilities. The executed prototypes demonstrate a constructive feasibility and architectural appealing. This development expresses the possibility to integrate 3D-printing in massive and varied dwelling construction, and suggests new paths for housing construction with the application of new design technologies and automated manufacturing in construction.

Keywords: 3D-printed construction; additive manufacturing; housing; architectural design; parametric programming

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1. Introduction

3D-printed construction is a new technology that allows to make elements for buildings by additive manufacturing of material, excluding the use of formworks, with short execution times, less resources, and a variety of shapes [1–6]. The manufacturing of the elements is usually executed by depositing a fluid mixture that hardens quickly (mostly cement-based), with a nozzle controlled by robotic arms or automated motors on displacement rails, through a printing path sent from a digital design. 3D-printed construction has emerged in recent years, with different equipment and materials, demonstrating its ability to make some construction components and full little buildings, mostly one-story [7–9] (Figure 1). This technology suggests important advantages in the reduction of construction deadlines and costs, decrease of waste, transportation, and work accidents; in addition, industrialization and specialization of the workforce, design versatility and performance optimization of buildings [10,11]. However, procedures are not yet consolidated, nor are construction systems massified.

Figure 1. Example of one story 3D-printed construction (Source: [12]).

3D-printed construction experiences have made it possible to make mostly self-supporting elements, such as furniture, planters, or one-story walls, due to the capacity to directly execute in one step, monolithic pieces of good strength and size [13,14]. Unlike conventional construction elements that require various accessories and tasks to be executed. Moreover, 3D-printed components usually have durability and stability, but little resistance to bending or traction stresses, so they would require additional reinforcements to execute load-bearing elements such as beams, lintels, slabs, walls, or columns resistant to lateral stresses. Several processes are being researched, but without a definitive solution [15,16]. However, the 3D-printed elements could be integrated with larger structures that provide the main resistant capabilities of the building, and to use pieces printed for other constructive requirements, like non-load bearing partitions and/or envelope.

The strategy to combine a main structure and partitions based on 3D-printed walls allows to erect residential buildings of different magnitudes and diverse housing organizations, defining diverse volumes with regular components, through modular forms, standardized reinforcement, and accelerated setting concrete. Combined with variable 3D-printed walls suitable for different climatic conditions and functional needs, to have a recurring management of the main characteristics of the construction, and a specific adaptation to the various housing requirements. The design of the housing units can be defined after the main structure, and taking advantage of digital control, even be adjusted during execution, to allow interaction with users and get different architectural expressions. Furthermore, this could consider future modifications, facilitated by the independence of the walls from load-bearing requirements and the reuse of materials for additive manufacturing.

The structure proposed for buildings that can accommodate 3D-printed walls must have a versatility in the total magnitudes, to allow its application in different circumstances (size of the site, amount of investment or local needs). As well as the adequate resistant capacities with a minimization of vertical elements, which allows the integration of variable walls. In Chile, as in other seismic zones of the world, the structural conditions of buildings have been increased to ensure their resistance against earthquakes; as well as the envelopes have been regulated for adequate energy performance and interior comfort for different climate zones, increasing construction costs and deadlines, as well as restricting designs in the face of growing real estate demand in the main populated areas [17].

The objective of this work is to develop a repertoire of residential building structures to accommodate 3D-printed walls, based on conditions for Chile, which presents a relevant climatic variety, real estate production and seismic requirements. Through an exploratory methodology, which consists of the formulation of a construction strategy based on the current conditions, the evaluation of the repertoire of designs according to surface capacities for the fulfillment of housing demands, the implementation of the parametric modeling procedure to verify its versatility, and the execution of wall prototypes to check their constructive feasibility and architectural appearance.

2. Background

Experiences with 3D-printed construction carried out during the last years have showed the execution of diverse components and experimental buildings, revealing several technological challenges [12,14,18]. The initial works with this technology has allowed to define deposition processes and material mixtures, tested with varied elements and specific building designs, in addition to discuss overall projections [8], with little formulation of construction systems or building processes. A few initiatives have suggested varied housing like a house made by pieces with the D-Shape printing technique [19] and the development of a high-rise residential building with printed envelopes [20]. Another work proposed a mobile printing system, called "ConPrint3D", with programming and execution phases [21]. The Army Corps of Engineers of the United States has also proposed a strategy for designing and printing military barracks, with executed examples [22]. Besides, the formulation of serial 3D-printed walls has established a design, evaluation, and execution process [23]. Likewise, the assessment of individual dwellings with 3D-printed construction has helped to define some general conditions [24,25].

A recent work proposes a shape-grammar that relates architectural designs to the 3D-printing execution, decomposing the elements of a building model for manufacturing considering its material deformation [26]. Other initiatives have proposed a workflow between the design and management of the 3D-printing, regulating the conditions of the shapes elaborated [27], and also the integration of BIM with the 3D-printing control, through the transfer of the digital model [28]. The BIM modeling and execution of the printing of a particular building have also been shown [29], the programming of various 3D-printed elements that can be analyzed in a BIM platform [30], and the comparison of printing strategies on-site or off-site by moving and assembling the construction elements [31]. In addition, workflows between the design, programming, and printing of components have been proposed [32,33]. A compilation of 3D-printed constructions reveals the diversity of designs and construction strategies, with some similar conditions [34]. However, architectural systems with 3D-printed elements have not been formulated.

Regarding structural reinforcements in 3D-printed construction today, it is possible to recognize 5 approaches: (a) material mixtures with fibers, cables or small pieces of steel, (b) printing of perimeters of elements with horizontal steel bars connecting sides, (c) printing of perimeters of elements with continuous vertical steel bars inside or (d) concentrated vertical bars, in both last cases with fillings of concrete, and (e) mixed structures of printed elements with steel profiles, wooden beams or conventional reinforced concrete for roofs, mezzanines or frames [35]. Most of the cases executed to date have one floor, mainly subjected to gravitational loads, and only some have two or three floors, combined with traditional structures [34]. This scarce development of reinforced 3D-printed elements for construction makes its integration in seismic countries, such as Chile, a major challenge, especially for high-rise buildings necessary for urban density and larger real estate complexes. Until now, there is a couple of declared cases of buildings built with 3D-printing in seismic zones, but there are no details of the elements used and seismic design of this type of structures.

The development of residential complexes with the combination of supporting structures and variable interior partitions has been proposed previously [36,37], suggesting to differentiate users and location. In last decades, housing design strategies to this aim has been proposed through digital systems with shape grammar approach [38], parametric analysis of decisions on BIM platforms [39] or through Web platforms with digital manufacturing of components [40], demonstrating the possibility of defining dwelling layout processes and managing construction, but without a constructive system defined.

On the other hand, Latin America has the highest rate of urbanization in the world and growing housing demand, addressed through various public programs and private developments [41]. In the case of Chile, the execution of housing settlements must consider a rising demographic and cultural diversity of its population, due migration, and socioeconomic transition [42], in addition to a wide climatic variety due to the longitude of its territory. This considers hot weathers in the north, seasonal conditions, and humid areas in the center, and cold zones in the south, requiring different thermal characteristics of the envelopes for their adequate environmental performance [43]. Furthermore, the frequent earthquakes in the country demand high-resistant structures [44], like many parts of Latin-America. All these aspects show the variety of requirements the housing market must face with high-demand and affordable costs.

Real estate construction in Chile and in most countries of Latin-America conduct a sustained production of huge dwellings complexes, mostly with identical houses or apartment blocks, to ensure low cost and speed construction [17]. The housing construction in Chile is currently concentrated in reinforced concrete high-rise and medium-rise buildings, with 75% of the residential supply [45], due to the high density of city centers and the need of resistant and durable constructions. These buildings are composed of large orthogonal blocks with central corridors and housing units on both sides [46,47]; arranged in isolation or composing two or three adjacent blocks, to minimize seismic efforts [48]. The blocks have regular widths between 14 to 18 m. to accommodate the interior circulation and a double housing bay with lighting and ventilation from the sides. Most of them with heights from 4 to 25 stories for an adequate real estate business in urban lots. There are also blocks of 3 or fewer floors, although in smaller numbers and with a more diverse organization, from single houses or terraced dwellings.

The multi-family buildings usually have a length of 30 to 80 m, and a height of up to 60 m, and width and length ratios between 1.5 to 2 and height and width between 1.5 to 2.5 are recommended, for an adequate size of elements resistant to seismic forces [46]. Since Chile has a high seismicity, usually several structural axes are defined, composed by walls, which are between 20 and 25 cm thick, every 5 to 6 m or less, with vertical continuity between floors. Residential buildings are usually configured with two parallel walls in the longitudinal center of the volume, defining the circulation between dwellings, and shorter transverse walls, which generate the division between units or sections, and partial walls or walls with windows on the perimeters (Figure 2) [47–49]. Therefore, load-bearing walls usually reach between 2.5% and 3% of the building's surface in each orthogonal direction (x; y), that is, 5 to 6% of the total, with high-quality concrete and nourished reinforcement, especially on the lower floors [50]. This consumes a significant part of the construction cost and its execution time, as well as the environmental footprint, transportation, and safety labor risks.

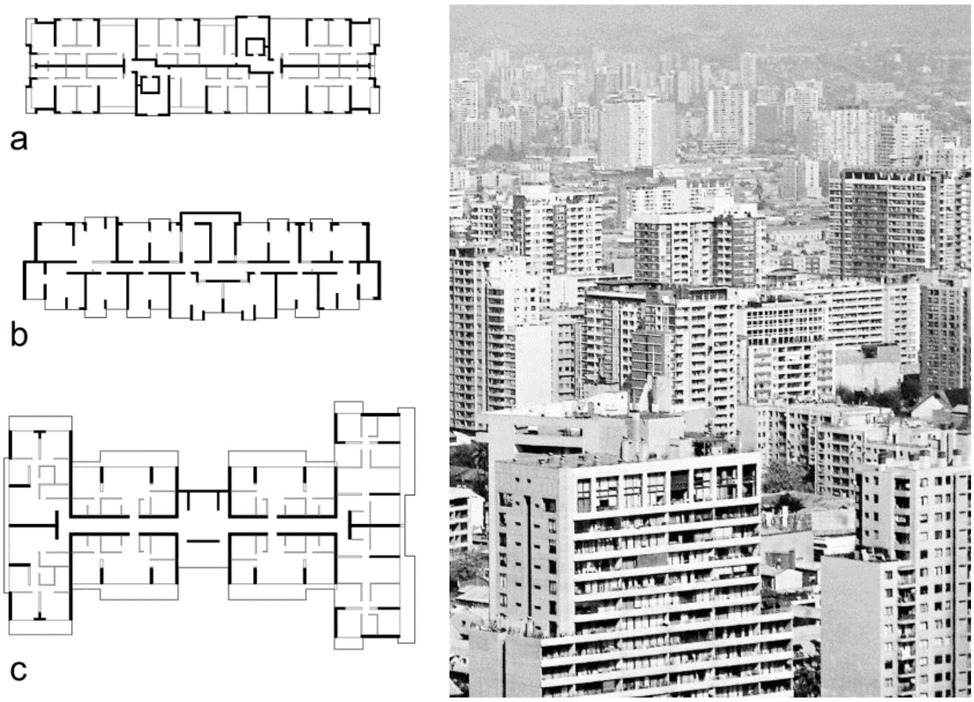


Figure 2. On the left, typical structural plans of residential buildings in Chile, a) with two vertical circulations, b) and c) with one vertical circulation and a central horizontal circulation (adapted from [44,51,52]), on the right, picture of buildings in downtown Santiago (adapted from [53]).

Residential buildings have different total amounts of apartments according to their individual surfaces and general volume, with housing units from 30 to 80 m^2, and some up to 140 m^2 or more. They are arranged on the continuous sides in sections of 6 to 20 m, totaling 12 to 18 units per floor, and up to 300 to 500 apartments in total [54]. The rooms are divided with load-bearing walls or light-weight partitions, approximately 50% each one due to seismic requirements, with a similar organization in shapes and dimensions. This generates a relevant rigidity in the housing distribution, as well as in its lifetime, which must be planned well in advance of the execution and can hardly be modified during its development or occupation. In addition it provides repetitive designs withextensive and monotonous interior circulations. Most of the time the units have only three or four variations in size or distribution, with similar bedrooms and bathrooms, and occasionally some balconies or terraces. Furthermore, this creates a regular and anodyne facade composition, which generates a precarious living and social alienation [55].

On the other hand, housing in Chile must adapt to different climatic zones [43], with regulation about different sizes of openings and material conditions for floors, roofs, and walls, with maximum total thermal transmittances from 0.35 $W/(m^2{\cdot}K)$ in the cold southern end up to 4 $W/(m^2{\cdot}K)$ in the hot north desert, besides the regulations for acoustic and fireproof insulation, and structural behavior. The dimensions of the living spaces are variable (with minimum measures for state-subsidized housing) but regularized by real estate production. This is accompanied with a strong demographic transformation, due to a rapid reduction in the birth rate, population aging, change in family organization, decrease in inhabitants per dwelling, growth in external migration and cultural diversity [42]. A similar context as several Latin American countries.

3. Materials and Methods

3.1. Design Conditions of Buildings Volumes

To define residential buildings that combine a resistant structure and 3D-printed walls, with a diverse capacity and adequate to the real estate requirements in Chile and other similar countries, first design conditions are established, and its modeling, variety, programming, and applicability are reviewed. The construction strategy composed of a main structure of reinforced concrete slabs in each floor with columns and some load-bearing walls to ensure its seismic behavior, and 3D-printed walls for partitions and outdoor envelope that allow different housing distributions, climatic adaptations, and architectural appearances. With a variation in the size of buildings, which allows covering the diversity of the residential production.

The structural grid is defined by a three-dimensional fabric, with distances between axis according to the resistance of regular elements and usual size of the housing spaces (Table 1). In the horizontal plane with axes every 6 m in the main direction along of the volume and 3 m in the longitudinal direction (composing modules of 3 × 6 mts with a surface of 18 m^2 each one), plus a one-meter projection on the outdoor sides, to expand the occupational capacity and formal variation, and 2.75 m of height between floors. Thus, the main structure is composed by reinforced concrete elements of regular sizes; 20 cm. height slabs in each horizontal level (perforated in vertical circulation places), 30 × 50 cm. beams in each axe, 30 × 60 cm. columns where the axes meet, and walls of 30 cm. width in some sections, both continued vertically.

Table 1. Design Conditions of the Building Volumes.

Number	Description	Characteristics
1	Structural Grid	Transversal distance: 6 mts. Longitudinal distance: 3 mts Height between floors: 2.75 mts Floor perimeter: more 1 mt
2	Total Length	1 to 24 modules of 3 mts
3	Total Height	1 to 25 floors
4	Total Width	1 module until 3 floors, 2 modules more central circulation from 4 floors
5	Structure	20 cm. Slabs, 30 × 50 cm. columns and 20 cm. width walls
6	Vertical Circulation	Inside housing units until 3 floors A double core from 4 modules length and 4 floors Two double cores from 18 modules length
7	Load bearing Walls	Perimeter of vertical circulations Skipped sections on side of central circulation
8	Partitions and outdoor envelope	3D-printed walls

For volumetric variation, a longitudinal progression of the structure is defined from one module to twenty-four (equivalent to 5 to 74 m long, with balconies in the perimeter), and in height from one to twenty-five floors. These magnitudes consider controlling structural sections, since larger dimensions can have seismic oscillation magnitudes that could require bigger elements or more complex arrangements. Specific conditions are contemplated for the indoor functionality in the different extensions. In buildings with one to three floors height, a single module along with projections in both sides is considered (8 m in total width), to form housing units by relating the levels with staircase inside each unit or outside the buildings. From 4 to 24 modules with a middle module open in the center for vertical circulation. From the four stories high, two transverse modules are contemplated, with a central circulation module of 2 m to axis, considering therefore a total width of 16 m of the volume. In turn, in lengths greater than 6 modules (18 m), a central core for stairs and another in front for elevators are considered, with load-bearing walls on the perimeter (with access openings). From 18 longitudinal modules (56 m) two cores are arranged, at equidistant distances from the ends. Also considering longitudinal load-bearing walls in the sides of circulation in skipped sections. On the other hand, volumes that have a side with a width less than half the height are excluded, since the slenderness can produce excessive seismic oscillations and little functional utility.

Several models in BIM software (Autodesk Revit 2021, San Francisco, CA, USA) are done with the application of different design conditions, in order to review its elaboration with regular building elements, and to perform quantifications and some examples of housing units' design. Including straight and curved walls to define 3D-printed partitions and envelopes, with different insulation, finishing and openings.

3.2. Evaluation of Residential Capacities

To evaluate the living area capacity of the designs defined by the construction strategy and volumetric variation, the following indicators are considered, which are usual in the housing planning.

(a) Total Built area: horizontal area of each floor from the outer edge of the slabs (including circulations and all interior elements)
(b) Total Livable area: horizontal area of each floor for private residential use, with half of the perimeter slab projections (considering the rest as balconies) and excluding the common circulations (corridors and stair/elevator cores)

From these values and considering the structural framework, the potential number of housing units and different types of dwellings are determined. These values are compared with the regular real estate production.

Also, the wall horizontal section area of the load-bearing elements is quantified, to compare them with usual values of the residential buildings in the country, which reveal amounts of material used in that construction part. And the horizontal surface of load-bearing and non-load bearing walls (partitions or envelope) per story according to some layouts proposed, to compare their proportions with regular residential building, to review the possibility of different organization and changes in time. The number of similar structural elements (with the same geometric dimensions) is accounted for some building models, since those involves formwork installation, concrete pouring in different locations and construction planning, and coordination. To review the relationship of construction regularity and housing layout diversity achieved by this strategy and design conditions.

Besides, some buildings models were completed with architectural details and furniture, to generate outdoor and indoor views, and interactive virtual walkthroughs to review possible occupancy and architectural appearance, compared with current residential buildings.

3.3. Programming of Design Generation

The volumetric repertoire, the distribution of residential units and definition of toolpath of the 3D-printed walls are implemented in a parametric programming to elaborate an integrated design process, which links the housing planning with the architectural development and the control of the building execution. The process regards a chained sequence from the general definition of the building volume, advancing in the detailing of elements and spaces, which integrates the different design conditions, up to the definition of constructive procedures. The initial stages are determined by the site and local regulations, as well as the magnitude of the real estate investment or housing planning. The intermediate stages of defining the housing units and rooms are determined by the dwelling program and habitability conditions, but also could be by specific requirements of the occupants, including the local climate and adequate energy performance. The more detailed stages are determined by the constructive capabilities of products, materials, machinery, and processes.

The parametric programming of design generation is implemented in Rhinoceros software, with the Grasshopper graphic language, through different components, links, and numerical controllers, in six main steps (Figure 3). Including the generation of 3D-printing code with Kuka-PRC and integration into BIM platforms through Rhino.Inside (Seattle, WA, US). Revit to transfer geometric information in the general development of architectural design and specialties. The evaluation of the parametric programming is carried out with the generation of examples with different values, reviewing the geometric consistency and detailing according to the design conditions, based on the numerical results and graphic views. As well as the export of data to test in different software and 3D-printed execution.

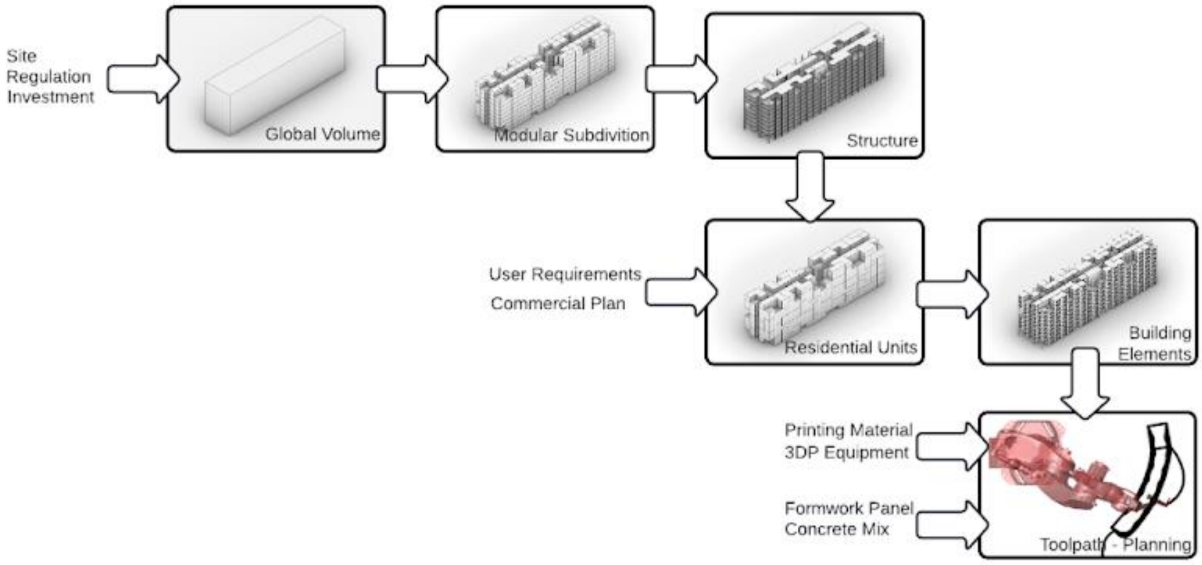


Figure 3. Overall flowchart of the parametric programming.

3.4. 3D-Printing of Wall Prototypes

The building considers a combination of a conventional resistant structure and 3D-printed walls. The main structure is defined with slabs, beams, columns. and walls in reinforced concrete type C25, according to the established grid. This corresponds to a usual construction procedure in Chile and many countries, with similar elements in shape and dimension, which should make it easier to execute. On the other hand, 3D-printed walls constitute a new technological capacity that has been experimented with in different parts of the world [7–9], but must be verified locally to check the capacity of the materials and processes. For this reason, wall prototypes were executed with a Kuka R120 2500 robotic arm (Augsburg, Germany) and a 120-L, 45-mph PFT Multimix Concrete Pump (Iphofen, Germany) at the Construction Technology Research Center (CITEC) of the Universidad del Bío-Bío, in Concepción, Chile. In addition, 3D-printed scale models were made in PLA plastic, to review some shape conditions, execution sequence and integration with the main structure.

To make the 3D-printed wall prototypes, different segments of building designs were chosen to establish a similar execution process and review different conditions. The constructive features of the walls were based on the 3D-printing procedure as well as material requirements for housing in the most populated areas of Chile (for thermal, acoustic and fire-proofing insulation). Also considering the free-form capabilities to create novel but functional environments to live, and different surface finishes as well integration of regular building elements (like windows, doors, services, sealing). A workflow for toolpath programming and printing sessions were developed, defining people, conditions and resources involved. First, three partial pieces were made to test the procedure, and integrate interior supports and coating possibilities. Then, three walls of full housing height and reduced extension were fabricated, considering transportation details and joint actions. A printing mix was defined, a Portland-type cementitious-based compound, fine aggregates, and a plasticizer additive. Finally, the material results of the execution were verified by measurements and visual verification in different parts and periods of time, in addition to carry out queries and interviews with people not related to the construction sector to collect an appreciation of architectural attributes.

4. Results

4.1. Modeling of Design Conditions

The design conditions established allowed to elaborate in BIM software different alternatives of buildings models with the main structure defined and overall sizes according to the number of modules and floors, generating volumes of increasing magnitude (Figure 4). The grid allowed to locate structural elements, related to the grid and levels, and develop different structural layouts based in the ranges set. The models generated are consistent in the geometry and constructive description, which allows to schedule dimensions, surfaces, and number of elements; as well as to incorporate other building elements (walls, windows, staircase, finishing, services, etc.,) and to generate plans and perspective images from different point-of-view and rendering.

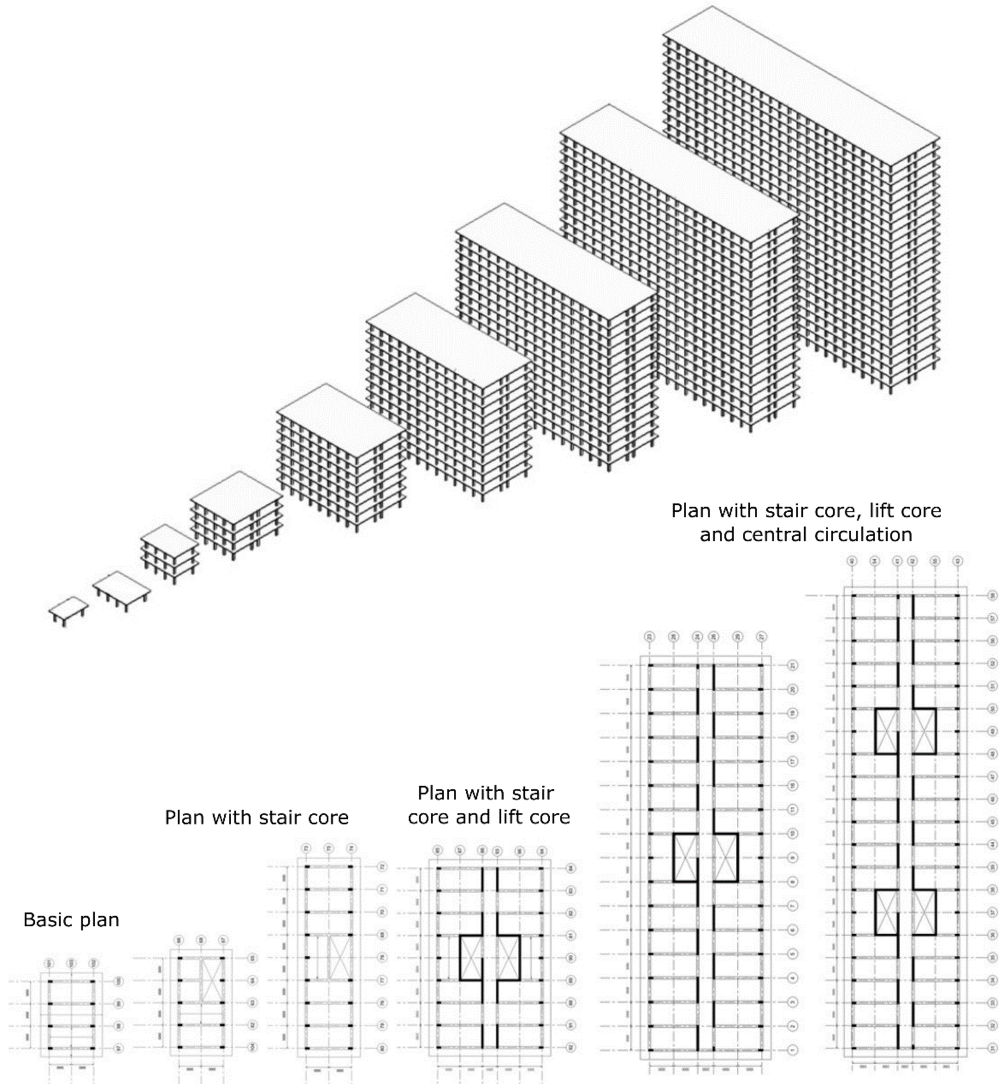


Figure 4. Examples of the proposed structural layout and its variations in plan and volume.

The buildings modeled with the main structure generate large open spaces that allow to elaborate different private rooms, private or common circulations and a variable occupation border. The smaller models have main spaces with all sides connected to the outside and the possibility of being integrated or separated, on the same floor or different levels, considering exterior staircases or interior with regular perforations in the slabs. The buildings of intermediate and larger sizes, provide a vertical and horizontal circulation space that can differentiate the occupation of the extensive sides. Including separated private spaces and relationship to different outdoor edges, but also transverse and longitudinal integration, as well as vertical. This allows conventional distributions of housing units (flats), or more unique distributions, with large apartments at the ends or related to two sides- It also includes units with various heights and an indoor staircase (duplex or triplex). All of these combined with small apartments, or shared indoor areas for services, collective work, or recreation, in addition to private or shared terraces or open spaces.

The models allow to incorporate partitions and outdoor envelope with elements of walls to define diverse housing units and rooms. Furthermore, it includes openings, windows, doors, shelves, among other, to schedule the spaces and elements included to check functionality and requirements (Figure 5). In addition, to establish different construction materials in the elements to schedule quantities and planning tasks. It's possible to define diverse layout of walls, in orthogonal, diagonal or curves, although some of the related components must be modified. The models show versatility to include elements, but several adjustments and checks must be done in the process to ensure integrity and achievements. For instance, connection between walls, location of services, room layout to accommodate furniture and activities.

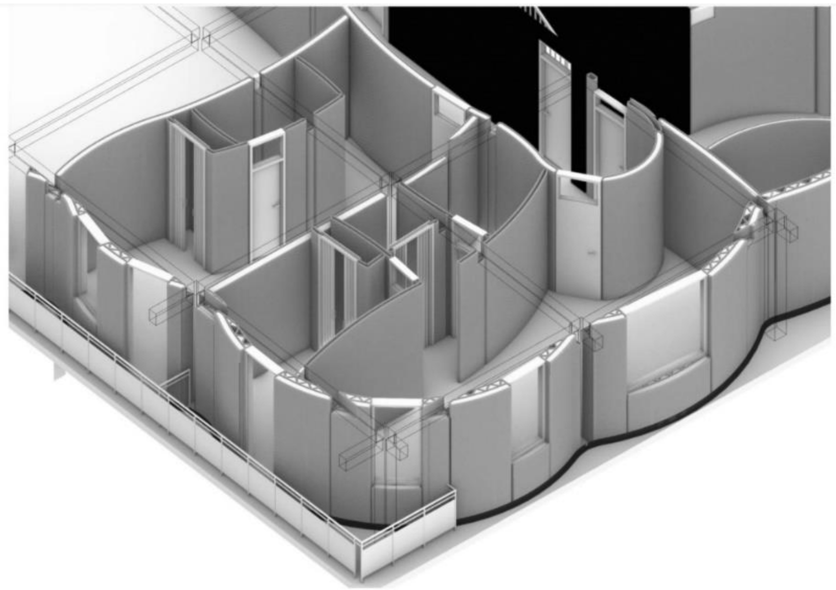


Figure 5. Example of a building model with indoor partitions and outdoor envelope with 3D-printed walls (Source: authors).

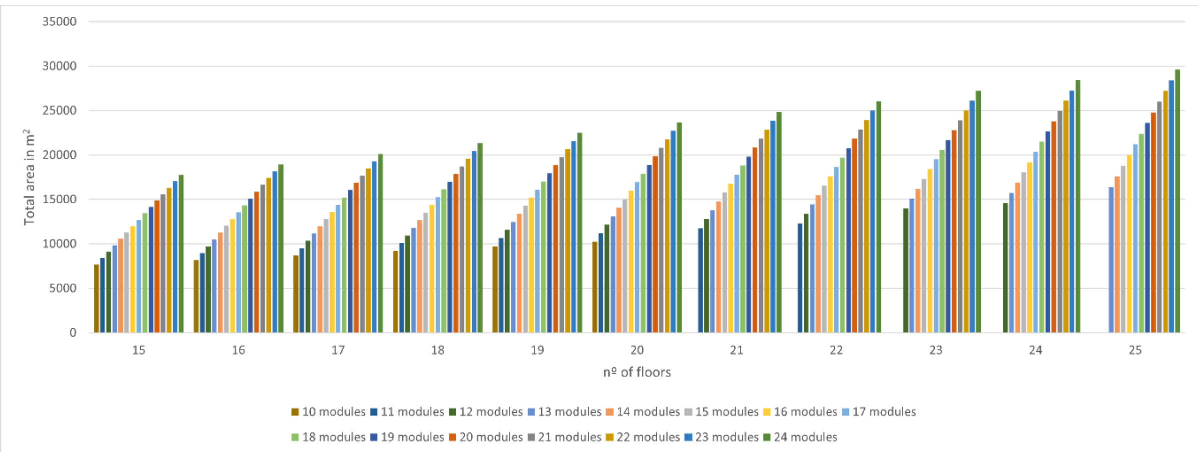
4.2. Evaluation of Residential Capacities

The building designs are diverse, according to the horizontal length (number of modules) and height (number of floors), maintaining a rectangular shape. The designs vary from 1 to 24 modules in length (5 to 74 m) and 1 to 25 stories high (3 to 75 m). Due to the conditions of functionality and structure, five main ranges of designs are produced (Table 2). The volumetric variation allows generating an initial repertoire of 600 building shapes of progressive length and height according to the defined conditions. 106 volumes that have excessive slenderness (width to height ratio on one side) are discarded, leaving 494 valid building designs. These have a total surface that varies from 40 m^2 to 29,600 m^2; and corresponds to a living surface from 40 m^2 to 23,000 m^2. This represents the usual size of a small home with one or two bedrooms, to a dwelling block with up to 400 apartments of 60 m^2. These correspond to a large part of real estate buildings in Chile [17]. Larger settlements can be composed with several blocks or combining different building volumes, including dwelling types.

Table 2. Design Conditions of the Building Volumes.

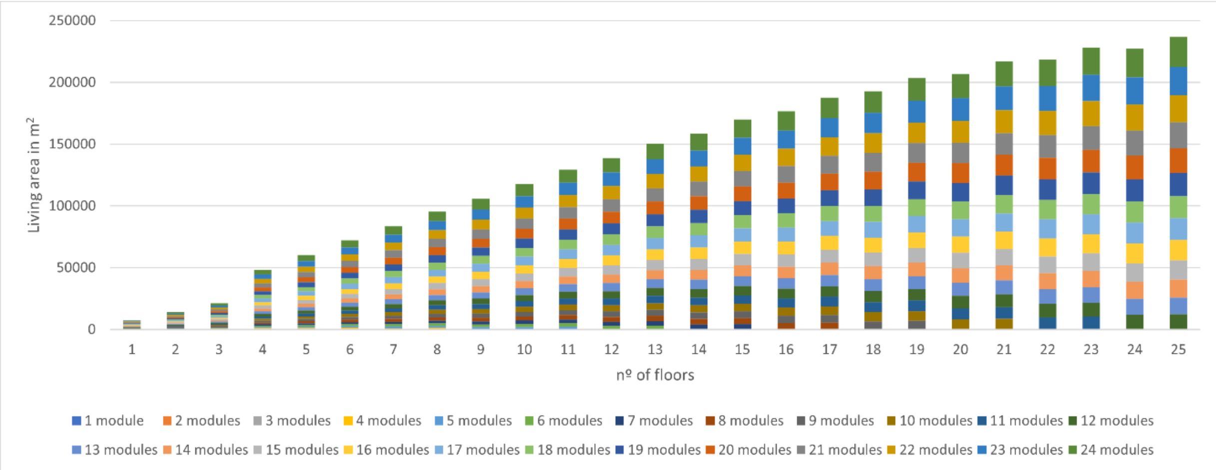
Ranges	Variations	Characteristics	Total Surfaces
1	1 to 3 modules and 1 to 3 floors	One module width, with private circulation or external	40 to 192 m^2 built
			29 to 180 m^2 living
2	4 to 17 modules and 2 to 3 floors	One module width and one vertical circulation	224 to 1,272 m^2 built
			188 to 1,218 m^2 living
3	18 to 24 modules and 2 to 3 floors	One module width and two vertical circulations	896 to 1,776 m^2 built
			824 to 1,668 m^2 living
4	2 to 17 modules and 4 to 25 floors	Two modules width, public central circulation and one vertical circulation	512 to 21,200 m^2 built
			304 to 17,650 m^2 living
5	18 to 24 modules and 4 to 25 floors	Two modules width, public central circulation and two vertical circulations	3584 to 29,600 m^2 built
			2848 to 24,100 m^2 living

The total built and living area of each building model has a stepped progression, based on the combination of number of modules in length and height in floors (Scheme 1). Then, a particular surface can be developed with several building designs, in different lengths or heights to be accommodate to diverse sites, local regulations or conditions. There are more alternatives in little surfaces, which correspond to more frequent and diverse residential buildings. The variety is reduced in bigger surfaces, by the exclusion of slender volumes, but in any case, there is a relevant diversity (for example, for 20,000 m^2 there are building designs of eight lengths possible).



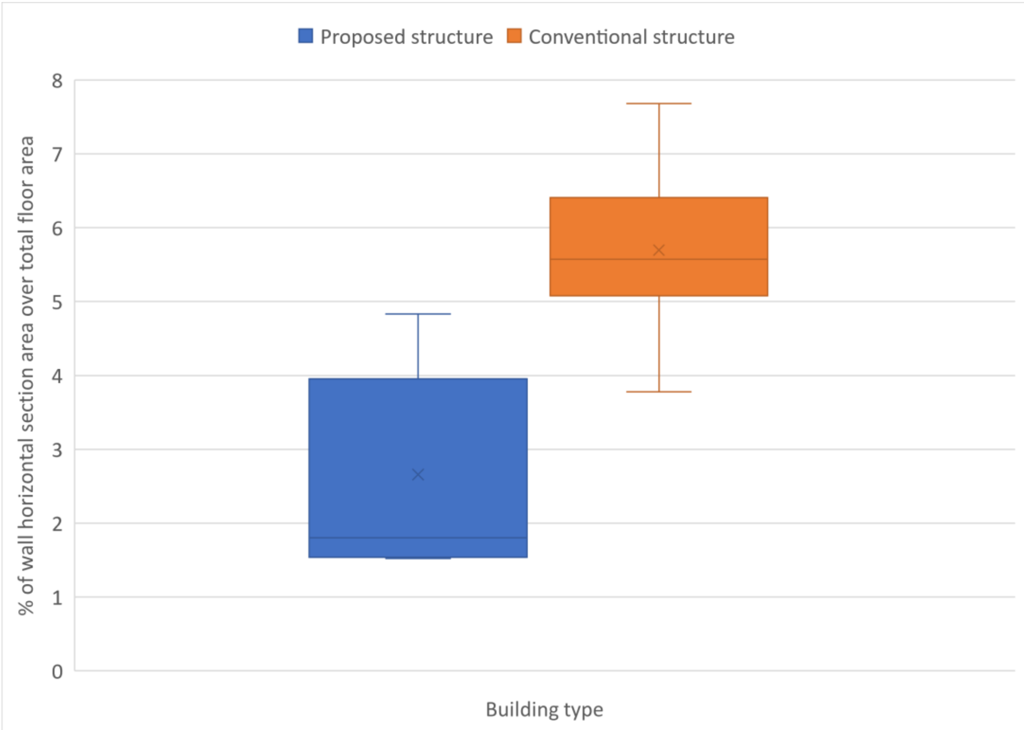
Scheme 1. Total built area of building models between 15 to 25 floors (Source: authors).

The generated designs have a ratio of total living area (excluding circulations and part of the borders) to build surface around of 85%, lower in bigger buildings sizes but similar to the current ones (Scheme 2). Each structural module has between 18 to 29 m^2 (according to borders) with at least one side to outdoor and one side to circulation or close ground level and can accommodate a little dwelling like a studio or one bedroom flat. Then, the number of potential housing units per building can be the number of modules for little dwelling, and the volumetric variety covers from 1 to 1,200 total units per building. As well as, for regular two-bedroom flat of around 60 m^2 such be developed in three modules, the volumetric variety can be 1 to 400, and larger flats can be in more modules and shorter ranges. However, this proposes a relevant variety and high possibilities of combination, larger than usual real-estate buildings.



Scheme 2. Total living area of each building model according to number of floors and modules (Source: authors).

The wall horizontal section area results different for each building model according to sizes and range of design conditions (Scheme 3), but, on average, represents 1.5% to 4% of the total floor area, which is significantly lower than conventional buildings in Chile, which can go from 5 to 6.5% [46]. This implies a reduction of about half of the material and structural execution, which results in relevant cost savings and shorter execution times. Besides, since the design is modular and uses mostly the same types of structural elements, considering walls and beam sections, and slabs thickness. While conventional buildings usually have several walls with different lengths and/or thickness. This regularity means the formwork, steel bars, concrete pouring and foundations can be prepared and executed with more celerity and cost reduction, and in some cases re-use of formwork can be coordinated with other buildings at the same time, increasing their productivity. It could also be easier to develop this structure in prefabricated concrete. In addition, the smaller ratio between wall horizontal section area and livable area in the building models allows bigger flexibility in the units' layout. The possibility to use non-load-bearings partitions and develop different housing layouts that could be customized according to the users' needs and even consider future modifications. Furthermore, this adds diversity for the dwelling types, shapes, thermal envelopes, and architectural appearance, to give more local adaptation and identity (Figure 6). This combination of regularity in the main structure and diversity of housing layout can support the execution and applicability of this construction strategy.



Scheme 3. Comparison of the ratio between wall horizontal section area and floor area in buildings with the proposed structure vs. conventional structure (source: Authors).

Figure 6. Rendered view of outdoor and indoor spaces with main structure of reinforced concrete slabs and columns, and 3D-printed walls (Source: authors).

4.3. Implementation of Design Generation Programming

The programming of design generation was carried out in Rhinoceros® software (Seattle, WA, US) through Grasshopper® (*GH*) algorithmic programming platform. Several sub-tasks were defined.

4.3.1. Generation of Global Volumes

It establishes the global volume of the building as an orthogonal prism or parallelepiped, with Vol_x, Vol_y as the horizontal lengths and Vol_z as the vertical length. These main dimensions are the result of simple equations regarding the number of structural modules *U*, *V* and *W*, the lengths of the module Mod_x, Mod_y, Mod_z in every Cartesian dimension, plus the Terrace Extension or T_{ex}, the Corridor Width A_p and Upper Floor Height U_{fh}. Then, the global volume is defined with the following equations:

$$Vol_x = 2\ (UMod_x + T_{ex}) + A_p \quad (1)$$

$$Vol_y = VMod_y + 2T_{ex} \quad (2)$$

$$Vol_z = WMod_z + U_{fh} \quad (3)$$

This step is then executed with the *GH* native BOX component (X_{dom},Y_{dom},Z_{dom}), with dimension controllers that ensure its size and subsequent decomposition.

4.3.2. Generation of Modules and Specification

In this step the dimensions and volume quantities described above are applied for the subdivision of the global volume, which is executed with GH native component Domain Box. This is produced in a division sequence, starting with the Y direction division in seven portions or thick layers of the global volume for the primary definition of the programmatic use (see Figure 7).

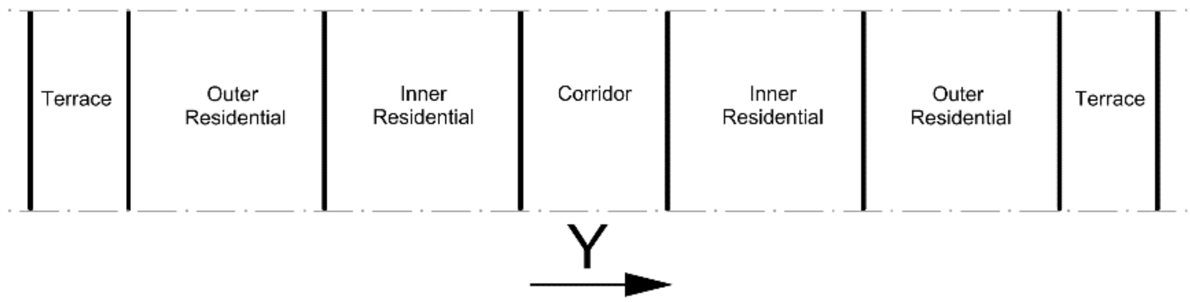


Figure 7. First subdivision across Y direction (Source: authors).

After this procedure, the seven portions are divided through X and Z directions according to the previous dimensioning, obtaining whole building modulation and resulting in individual volumes for residential modules, corridors, and terrace spaces. Once this is defined, specific and vertically aligned Inner Residential parts are taken as nuclei of vertical circulation and elevators, in a modulation according to building apartment quantity and length in the X direction.

4.3.3. Development of the Main Structure

This stage establishes the load-bearing structure by defining slabs, walls, and columns, from the modulation carried out by the previous stage and the measurements defined. Every module was conceived to incorporate these series of volumes, so main shape will not be altered. Main structure consists in several parts: Walls, columns, and slabs.

- Walls from each module adjacent to the corridor are taken alternately as structural in the X dimension. Every face around the vertical connector is taken also as structural Wall. This pattern repeats through the entire building height.
- Columns are located on each vertical edge of the Outer Residential modules. This pattern repeats through the entire building height.
- Slabs are defined by giving a thickness to each lower horizontal face of each module to the inside.

This process generates a new sequence of shapes, which correspond to the main structural pieces, ordered by level and position. Which are dependent on the general volume and can be controlled for their specific dimensions.

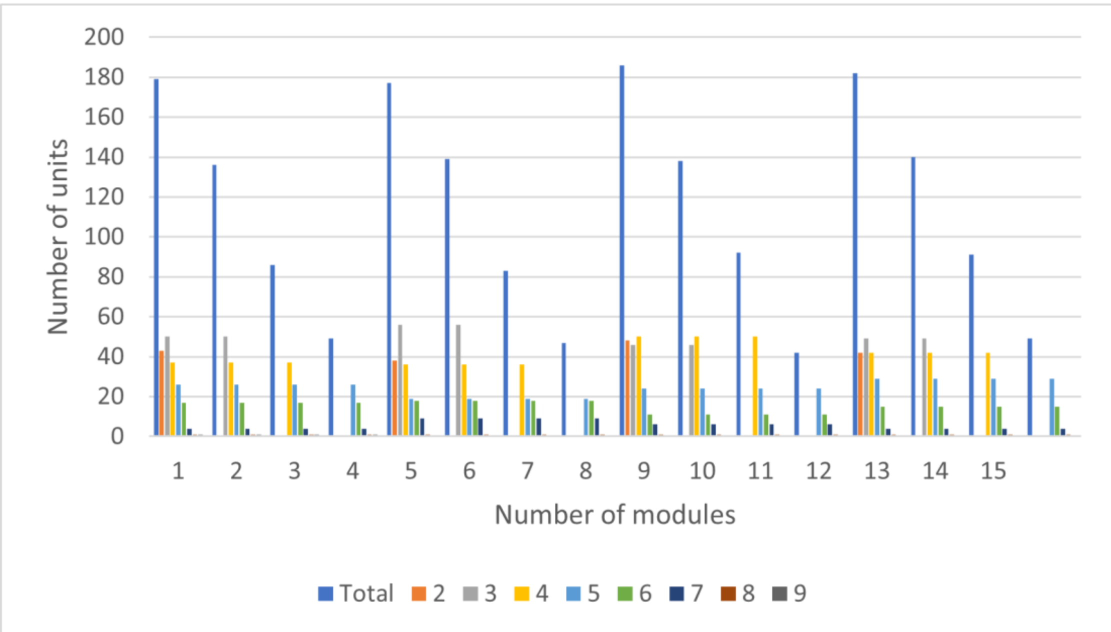
4.3.4. Distribution of Residential Units

This step settles dynamically the location and composition of departments or housing units, resulting in a disparate set of residential modules in a settled range across the different modules and floors of the building.

This dynamic algorithm, based on Kangaroo 2® plug-in (Seattle, WA, US), will vary out housing constraints modules occupying main volume and displacing the others, allowing also manual yet dynamic modification. The general restrictions of the procedure that leads to preserve the architectural program are:

- Each group of modules has at least 1 spatial unit adjacent to the corridor (this unit will correspond to the access area or hall, plus kitchen and bathroom.
- Nearly half of the modules will be adjacent to the exterior façade.
- The most aligned module with the access level will be assigned as a common area.
- Each group of modules may not exceed 3 floors in height.

This procedure generates different orders that can be established randomly and evaluated later, or either accept some weights for existence (i.e., 20% 6 module housing units, 40% 4 module housing units and so on) that can be easily represent diverse functional demands (Figure 8; Scheme 4). At this stage, indicators are available for individual, total and programmatic quantification of resulting surfaces.



Scheme 4. Total housing units included in each alternative by number of modules (Source: authors).

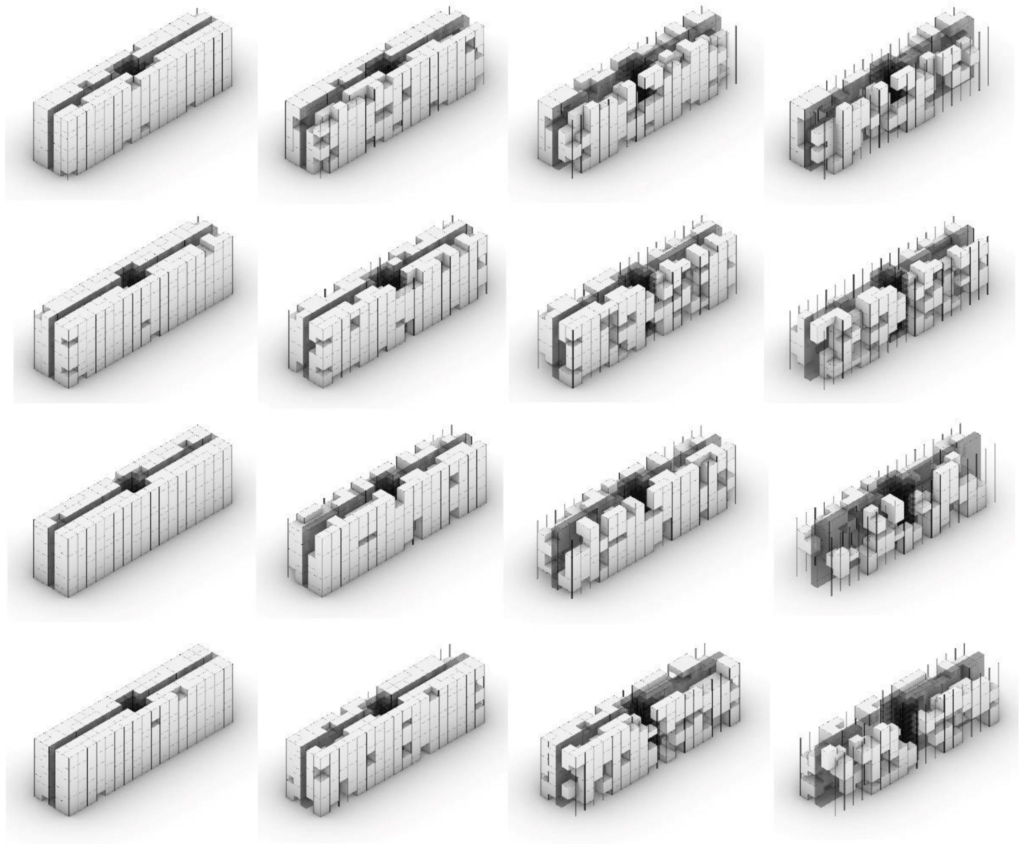


Figure 8. Programming results showing alternatives of modules distributions of housing units, including open spaces (Source: authors).

4.3.5. Elaboration of Partition

By evaluating the geometric situations of the modular sets of each department and their component faces, a Shape Grammar-type algorithm is established that propagates 3D printed components, forming the dividing walls with different horizontal curvatures, based mainly on current robotic manipulator kinematics. Some of these recognized situations are:

- Outer shells of the departments.
- Adjacencies to perimeter or corridor.
- Interior faces according to program.
- Faces adjacent to other departments or unused interior spaces.

These situations will be crossed with different generation relationships considering encounters between two surfaces, between three or more surfaces, etc.

4.3.6. Toolpath Generation and Print Files

For the execution of each 3D-printed element, the corresponding wall is first subdivided, according to the estimated geometric scope of the deposition equipment, considering the three Cartesian axis, with controllable variables. Then, through Kuka PRC, the printing trajectories with a horizontal slice of a height of 3 cm are generated, equivalent to the height of the bead of deposited material and a linear movement (LIN) along the perimeter of the upper ascending spiral element of planes to orient the tool with points every 5 cm, increased in the corners to smooth the turn. In case of considering openings or modifications of the bead, nozzle, surface texture or internal reticulation, they are integrated in the programming of the tool path and definition. These paths are generated as control files for the printing equipment with the work quadrant, start level and tool distance.

The programming executed can generate different alternatives of building models, according to the number of modules and floors defined, and diverse housing units' layouts, as well as structural elements and toolpath of 3D-printed walls. Additionally, this will allow to schedule quantities and export the geometric files to BIM software and robot to 3D-printing process. The files are coherent and detailed, although they must be completed with more constructive and architectural information, as well specific control to 3D-printing, according to material mixture and equipment used.

4.4. Elaboration of 3D-Printed Walls Prototypes

The prototyping of 3D-printed walls for this building strategy has allowed defining a design process and working conditions, as well as making some demonstrative pieces. The elaboration of the prototypes contemplated a phase of digital programming and another of material execution, with several activities each one (Table 3). For the programming, three digital volumes were first elaborated based on wall segments of the BIM model of one the building developed, making the definition of toolpath for printing trajectories. The three wall prototypes were established with a residential height (2.2 m), with a length within the reach of the stationary robotic arm with base platform and considering a slight curved shape, and thickness with double hollow cord and separations with 8 mm diameter iron bars. placed every 15 cm. (horizontally and vertically). These features were based on thermal and structural requirements usual for housing in the most populated areas of Chile, and free-form capabilities of printing process, but appropriate for living conditions. The first prototype with a basic radial shape and smooth finish; the second with a radial shape and a smaller recess for a window and a regular texture, the third radial with a larger recess and an irregular texture; to test increasing printing capabilities for construction elements. The programming was based on shapes in Rhinoceros, with a slicing and a linear spiral movement of planes for tool orientation with segments every 5 cm, increased at the corners to smooth the rotation. The work quadrant, start level and tool distance (nozzle) were also defined.

Table 3. Tasks developed for 3D-printed walls.

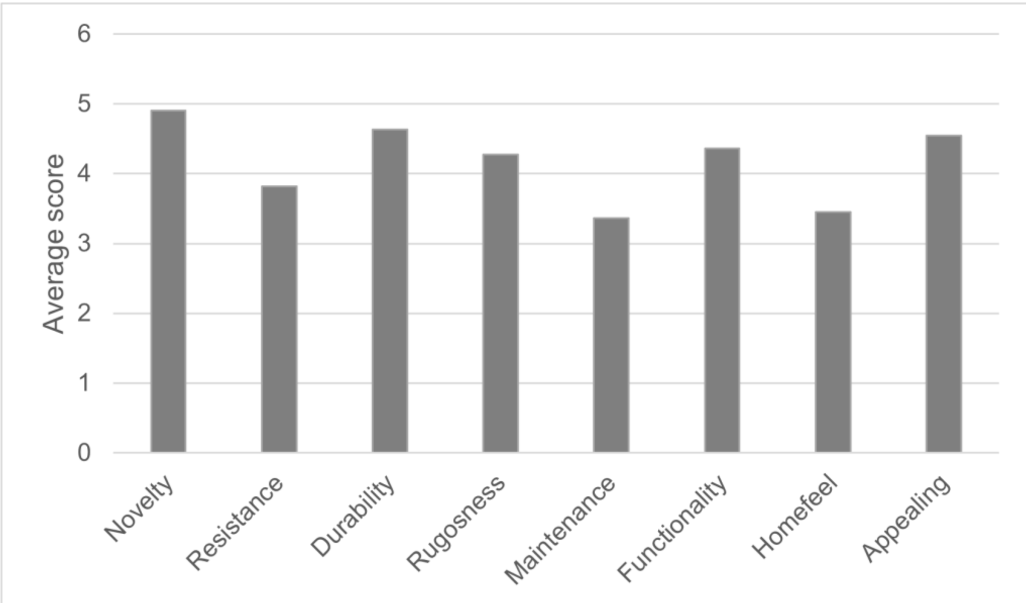
Activity	Resources	Result
BIM element	BIM software and BIM model of building	IFC file
Rhino shape	NURBS 3D-modeling software	SHP file
Slicing	NURBS 3D-modeling software	SHP file
Toolpath	NURBS 3D-modeling software and robot programming software	PRC File
Robot setting	Control robot software	G-code or proprietary file
Material supplies	Prepared mix or cement, aggregates and additives	Proper number of materials for the element
Control of Humidity	Control of humidity, slump and extrudability to set open time	Checklist of properties
Mix preparation	Mixer and pump, with water feed, hose and nozzle fixed to end effector of robot	Proper mix provided

The prototyping of 3D-printed walls involved several steps (Table 3). Two partial test pieces in low and mid-height were initially executed, and later the three complete elements (Table 4), through a dozen of sessions (since some of them were collapsed or interrupted). Four people participated in the execution; a designer-programmer who prepares the digital files in advance, make simulation of the process, estimates materials and work time; a robot operator to control the 3D-printing; and an operator in charge of mixing and pumping, with an assistant to place the iron bars. Considering the previous day of an initial preparation of the aggregates (separation and humidity verification), and at the beginning of each session a pouring and mixing in approximately one hour, while the working platform is installed, they verify the levels and programming with the robot. Each impression takes from 20 to 80 min, including the placement of irons with lateral markings, and is then kept in the same position for one day to ensure hardening, whose final rigidity is obtained after three or four days, according to compression tests. The mixtures used for the prototypes was a micro-concrete with approx. 700 kg.cem. /m3, fine aggregates and fluidizing additive. The deposition was made with a 25 mm diameter nozzle, resulting in a cord of approximately 20 mm high and 40 mm wide (with a slight settlement in the first cords). With a density of approx. 2200 kg/m3, the executed elements have weights of 200 to 500 kg each, equivalent to 20 MPa [56] (construction procedures were verified with specialists on each subject).

Table 4. 3D-printed wall pieces executed.

N°	Height (cm)	Length (cm)	Curve (degrees)	Width (cm)	Properties
1	19	109	40°	19	Coating
2	84	110	40°	21	Bars and Insulation
3	218	100	40°	21	Vertical stability and regular finishing
4	218	140	55°	26	Texture and minor opening
5	220	150	60°	26	Texture and major opening

The executed elements have presented adequate stability and durability, with a progressive discoloration due to natural drying (Figure 9). With a regular rough finish, and local anomalies. Items with surface textures have shaded variations. In the partial pieces of lower height, coatings (cork-based paints with different colors), thermal insulation fillers (injected polyurethane), drilling for installations and lifting transfers were tested. The sections of the walls have been tested for moving with forklifts, assemblies with sealants and placement of windows, roofs, accessories and fixing to the base. During a visit to the prototypes with a non-specialized public, the visual appreciation of the attributes of novelty, resistance, durability, roughness, maintenance, functionality, acceptance, and attractiveness was consulted, as well as open comments. The results of the consultation taken from 11 visitors were mostly positive, especially in novelty, durability, functionality, and attractiveness, somewhat lower in maintenance and reception, without differences between gender or age, and they commented on changing color or finishes (Scheme 5).



Scheme 5. Average socres for perception of 3D-printed wall attributes; 5 is very high and 1 very low (Source: authors).

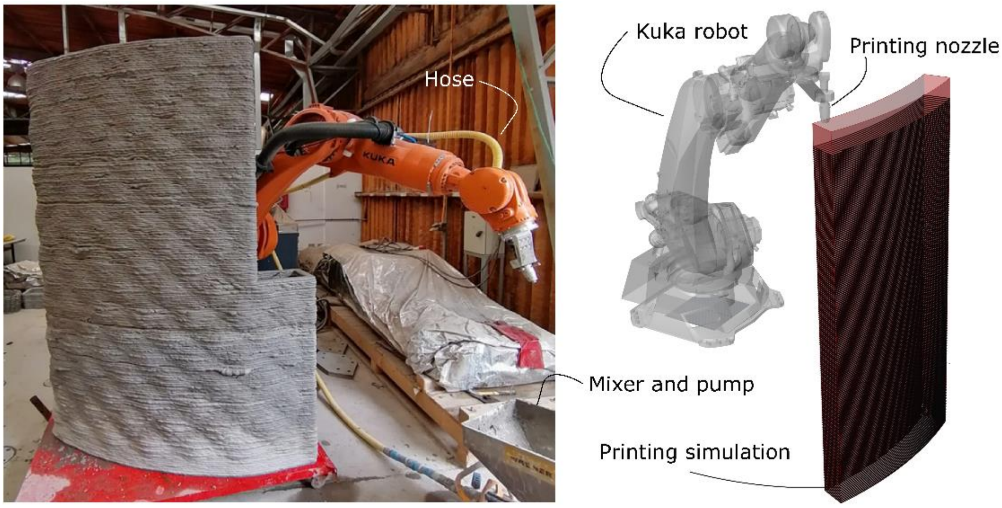


Figure 9. 3D-printed wall prototype executed (left) and previous simulation of the process (right) (Source: authors).

5. Conclusions

3D-printed construction or additive manufacturing presents promising possibilities in construction, but little progress has been made in its mass use due to the multiple development and implementation challenges. This work proposes a building strategy combining regular structures with 3D-printed walls, to take advantage of the most evident capabilities of this technology and integrate it into massive construction assuming some main requirements with traditional elements. The strategy is based on the separation of the resistant components from the partitions that do not support loads to elaborate them with additive procedures, which allows formal versatility. A progressive grid is proposed to distribute structural pieces and generate buildings with different sizes, which can accommodate very diverse housing distributions. The design procedure is programmed and modeled with different compositions, showing its spatial variability and architectural appeal. Various pieces of 3D-printed walls are executed to test construction capabilities and properties, verifying the feasibility of the construction strategy.

This similar approach has been previously proposed for residential buildings during the 20th century and has been implemented especially for offices and industrial buildings as "open plan" with light partitions, but scarcely in residential constructions that have higher habitability and resistance requirements, particularly in seismic countries. This proposal minimizes and regularizes the supporting elements (in slabs and a grid of columns and few walls of similar measurements), which facilitates their execution and subsequent integration, as well as implements them in a digital design system, which allows to program their variation. The programming can easily generate different alternatives for the general volumes, as well as for the interior and perimeter walls executed by 3D-printing.

This strategy also makes it possible to separate the management and execution of different magnitudes of building structure and partitions, facilitating the diversity and participation of the occupants. It also allows control of the construction, through the digital flow of information to the handling of manufacturing robots. In this sense, it suggests two differentiated scopes of development of the general volumes and the housing units, allowing to combine global productivity and local adaptation to individual interests and/or climatic conditions. Furthermore, providing an attractive flexibility and novel appearance. The modeling and programming of the digital design demonstrate the ability to implement and integrate the process, and the 3D-printed wall prototypes allow the material verification of the strategy to begin. The proposal must make substantial progress in its development and construction and operational testing, but it suggests new paths for housing construction and the effective application of new design technologies and automated manufacturing in construction.

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