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Development of a residential prototype using 3D-printed elements

Authors:

[1]Prof. **Rodrigo García-Alvarado**
rgarcia@ubiobio.cl
Corresponding author

[2]Prof. **Claudia Muñoz-Sanguinetti**
clmunoz@ubiobio.cl

[1]Assist. Prof. **Paula Ulloa-Aguayo**
pulloa@ubiobio.cl

[2]Assist. Prof. **Aracely Rocha-Rubilar**
arocha@ubiobio.cl

[3]Assoc. Prof. **Alexander Opazo-Vega**
aopazove@ubiobio.cl

[1]Assist. Prof. **Paulina Wegertseder-Martínez**
pwegertseder@ubiobio.cl

[1] Universidad del Bío-Bío, Chile
Department of Architectural Design and Theory
[2] Universidad del Bío-Bío, Chile
Department of Construction Sciences
[3] Universidad del Bío-Bío, Chile
Department of Civil Engineering and Environmental Protection

Professional paper

Rodrigo García-Alvarado, Claudia Muñoz-Sanguinetti, Paula Ulloa-Aguayo, Aracely Rocha-Rubilar, Alexander Opazo-Vega, Paulina Wegertseder-Martínez

Development of a residential prototype using 3D-printed elements

This paper presents the design and construction of a home prototype incorporating 3D-printed elements built in Chile. It provides a novel review of the process, which involved multidisciplinary planning, structural and environmental analysis, parametric design, and the printing of elements in a university laboratory, followed by on-site assembly and full construction. Compliance with local standards and the optimisation of activities is also examined. The study demonstrates the feasibility of developing housing with 3D-printed elements in the country, enabling architectural variety, local adaptation, and continuous improvement.

Key words:

3d-printed construction, parametric design, structural analysis, environmental analysis, construction management, architectural variety, housing

Stručni rad

Rodrigo García-Alvarado, Claudia Muñoz-Sanguinetti, Paula Ulloa-Aguayo, Aracely Rocha-Rubilar, Alexander Opazo-Vega, Paulina Wegertseder-Martínez

Razvoj prototipa stambenog objekta primjenom 3D tiskanih elemenata

U radu prikazana su projektna rješenja i izvedba prototipa stambene građevine primjenom 3D tiskanih elemenata, izvedenog na području Čilea. Rad donosi nov pristup analizi postupka koji je obuhvatio interdisciplinarno planiranje, konstrukcijske i okolišne analize, parametarsko oblikovanje te izradu elemenata 3D tiskom u sveučilišnome laboratoriju, nakon čega su uslijedili montaža na gradilištu i cjelokupna izvedba građevine. Također su ispitani usklađenost s lokalnim standardima i optimiranje aktivnosti. Istraživanje potvrđuje izvedivost razvoja stambenih građevina primjenom 3D tiskanih elemenata u zemlji, uz mogućnost arhitektonske raznolikosti, prilagodbe lokalnim uvjetima i kontinuiranog unaprjeđenja.

Ključne riječi:

3D tiskane zgrade, parametarsko oblikovanje, konstrukcijska analiza, analiza okoliša, organizacija građenja, arhitektonska raznolikost, stanovanje

1. Introduction

1.1. 3D printing for housing development

3D printing is a promising technology for housing construction due to its potential to reduce time and resource consumption, thereby improving productivity and sustainability [1-3]. Various processes and materials have been tested, leading to several experimental constructions. To date, more than one hundred examples of houses incorporating 3D-printed elements have been built worldwide [4-6], but execution conditions have yet to be defined, particularly for construction in seismic zones and diverse climates. This article presents a novel review of the design and construction of a housing prototype with 3D-printed elements in Chile, detailing its adaptation to local structural and environmental requirements while incorporating architectural diversity, based on the work of a multidisciplinary team.

1.2. 3D-Printed construction

Construction with 3D-printed elements is carried out using large gantries or robotic arms, supported by mixers and pumping systems that deposit a fast-setting fluid to additively create components at habitable height [7, 8]. The deposition of the mixture is controlled by a digital system, forming complete shapes through successive layers of boundary lines. This printing process differs from traditional construction, where elements are typically assembled using multiple components, various workers and tools, multiple packaging materials, diverse tasks, and additional support accessories. Consequently, this new process reduces activities, timelines, and material consumption while decreasing manual handling, accident risks, waste, and transportation. It also improves the level of detail and digital information flow, facilitating project management. However, several disadvantages and uncertainties remain [8]:

- Uncertainty regarding mass production and the properties of printing mixtures across different locations.
- The need to combine printed parts with reinforcements to ensure lateral structural strength and to create joints between printed components and other elements.
- Verification of the impact on execution and sale prices of constructions using 3D-printed elements.
- Evaluation of the environmental performance and ecological impacts of buildings incorporating 3D-printed elements.

1.3. Materials and standards for 3D-printed construction

To date, construction with 3D-printed elements has primarily relied on cement-based mixtures, which enable large-scale supply and exhibit the rheological properties required for extrusion and early hardening. These mixtures offer workability, good adhesion, and rapid compressive strength, allowing the creation of solid or hollow volumes with self-supporting perimeter walls [9]. Several international standards for construction with 3D-printed elements have been established [10-13], classifying systems and defining general characteristics, while additional standards for procedures and construction systems are under development [8]. University research in this field has generally focused on material properties, printing processes, and potential applications. Various companies and academic initiatives are developing specialised construction strategies, and some buildings have already incorporated 3D-printed elements [14, 5].

1.4. Application to housing

Construction with 3D-printed elements has primarily focused on wall execution, as walls are complex and time-consuming to build and are essential for defining spaces and built volumes [14]. In contrast, floor and foundation elements tend to be more massive and simpler to construct using low-cost equipment and materials, making 3D printing less advantageous. Likewise, roofing elements or components subjected to lateral forces, such as columns or beams, require greater flexural strength than current mixtures can provide. Consequently, additional reinforcements, such as metal bars or strips, are required. Moreover, services and finishes must be incorporated, meaning that 3D-printed elements constitute only part of the construction, albeit a significant one in terms of execution time and architectural configuration [6].

Housing is one of the most pressing global construction needs, distributed widely in small units that accommodate residents with diverse occupations and locations. Housing developments range from individually built homes to large-scale residential complexes and multi-storey buildings containing numerous similar units [15]. In many countries, housing production falls short of demand due to financial constraints, diverse conditions, high costs, and construction delays. This persistent housing shortage has driven the adoption of new processes such as 3D printing to accelerate production [16]. In addition, there is growing demand for environmentally sustainable housing that minimises its contribution to climate change. Technologies that allow greater control and efficient resource use are therefore well suited to reducing ecological impacts [1, 2].

This also requires adapting housing to different climates and interior uses, as well as to natural hazards. For example, Chile, with nearly 20 million inhabitants, produces approximately 150,000 housing units annually that must address diverse social needs and adapt to 25 different climate zones according to the Köppen classification. All are seismically active regions, resulting in strict structural standards, alongside varying thermal requirements and usage patterns [17, 18].

1.5. Global status of housing with 3D-printed elements

Over the past decade, approximately one hundred experimental houses incorporating 3D-printed elements have been constructed worldwide-mostly single-storey examples, with a few two-storey structures and a small number of housing complexes [6]. Most of these projects serve as test cases for technological strategies, although there is limited documentation on their development [4, 5, 19-22]. A few suppliers, such as COBOD, Cybe, Bemore-3D, WASP, and 3D-Constructions in Europe, offer standardised large-scale equipment for printing construction elements [14, 23]. Additionally, global suppliers such as Lafarge and SIKA provide ready-mix solutions for 3D-printed construction [8, 24]. Some developers, including WinSun in China and ICON in the United States, propose different designs and, in some cases, commercialise their constructions [14]. Among the housing prototypes produced, some have been printed on-site, using deposition equipment, mixers, and pumps installed directly at the location to print walls in continuous processes on top of previously constructed floors, sometimes incorporating steel reinforcements. In other cases, elements have been printed in factories, where equipment, mixers, and pumps are installed in protected warehouses to monitor production. These components are then transported to the site for assembly, combined with foundations, reinforcements, and joints. In both approaches, construction is completed with finishes, roofs, and installations. Some housing complexes have been built, but mass production processes have not yet been established.

Using Bemore printers-similar to the one used in this study-approximately ten experimental constructions with 3D-printed elements have been completed, including an initial prototype built in 2018 in Valencia (where the company originated) and another constructed in Morocco for the 2019 Solar Decathlon, along with several projects on Spain's southern coast [25, 26]. However, the overall production of houses with 3D-printed elements remains limited and dispersed. Most cases have been built in warm climates without seismic requirements and exhibit little architectural variety and minimal detailing [4, 5, 27].

1.6. 3D-Printed construction in Latin America

In Latin America, a small prototype was built in Colombia in 2016; a house with 3D-printed elements began construction in Brazil in 2022 (though its completion has not been documented); a one-room pavilion was completed in Guatemala in 2023; a few houses were built in northern Mexico in 2021 by the U.S.-based company ICON; and a basic construction was produced in Peru in 2024 [6, 28].

In Chile, the University of Bío-Bío has been experimenting with this technology since 2018 through a multidisciplinary team and support from local companies. Their work includes developing a 3D-printing mixture, installing large-scale equipment (notably a Kuka KR120 R2500 robot and, more recently, a Bemore Pro gantry printer), and manufacturing several components, culminating in the assembly of a covered cabin in 2023 (Figure 1). This initiative has been driven by national demands for industrialisation, productivity, and sustainability in the construction sector, as well as by persistent housing shortages. As a next step in this development, a housing prototype with 3D-printed elements was undertaken with the participation of private companies and the support of state projects, addressing the challenges of architectural diversity, seismic resistance, and environmental adaptation specific to Chile. This effort aimed to advance new housing possibilities in the country, resulting in the initiative known as "Casa Semilla" (Seed House), described in this article through a novel review of the experience and features adapted to local conditions.

2. Methodology

To develop the housing prototype with 3D-printed elements, aimed at disseminating and assessing the housing potential of this technology in Chile, a series of sequential activities was undertaken (Figure 2). First, the tasks and design requirements were defined and planned. Subsequently, the design, programming, and printing of the elements were carried out in the university laboratory, while construction work was conducted on-site with support from partner companies. The process concluded with the public exhibition of the prototype, followed by ongoing monitoring that will continue for one year.

Figure 1. Equipment and first works of 3d-printed construction in University del Bío-Bío, Chile

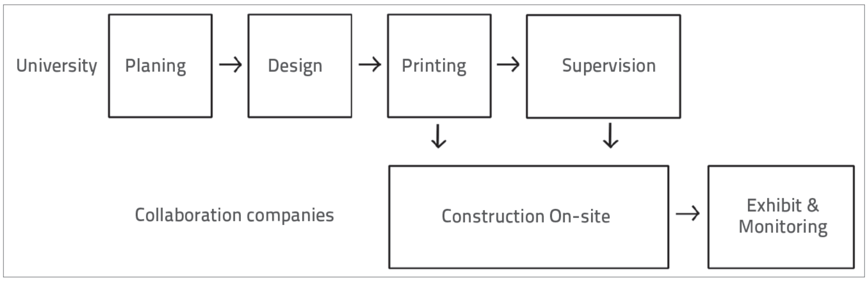

Figure 2. Sequence of activities

The process began with an agreement between the University and a real estate development company. The company agreed to provide the site for construction, to complete the prototype's building activities, and to support its exhibition. The University, in turn, committed equipment, personnel, and technical processes, primarily focused on managing the construction and printing of the elements, using available resources, staff, and tasks funded by national research projects. Collaboration was also established with several construction suppliers, who contributed materials, products, and technical advice. Subsequently, a detailed plan of tasks, resources, and scheduling was prepared, defining the participation of each entity, as well as the personnel, equipment, and materials required.

The general characteristics of the prototype were then defined to promote the technology and assess its feasibility in terms of seismic performance, environmental adaptability, and architectural diversity. A single-storey structure was selected, concentrating the printing on the walls to capitalise on the advantages of additive manufacturing in erecting vertical partitions and shaping the building's main architectural features. A system of load-bearing walls with a lightweight roof was adopted to reduce structural demands in a seismically active context, and the indoor area was kept small to optimise resources and remain within the printer's geometric range. A preliminary design was developed, combining straight and curved elements to demonstrate the formal versatility of 3D-printing technology, with a site placement that favours public exhibition and solar radiation capture to support sustainable performance. The interior layout was organised into three essential spaces (living room–kitchen, bathroom, and bedroom), with hollow vertical walls to accommodate climate-appropriate thermal insulation, structural reinforcements, and building services, while retaining the printed surface as the visible finish.

The initial design was refined through structural and environmental analyses, and construction details were developed in consultation with collaborating companies. Parametric programming of the architectural form was performed to explore major design variations, alongside programming of the printing paths, both using Rhinoceros-Grasshopper software and exporting to G-code for machine control. The design process employed SketchUp, AutoCAD, and Autodesk Revit, with seismic analysis conducted in the finite element software ETABS, environmental analysis using Insight, and visualisation through 3ds Max and Corona Render. Printing of the elements was executed using a Bemore-3D Pro industrial gantry with a geometric reach of 3.5 · 6 · 9 m (height, width, and length, respectively) and a PFZ 3.5 Kp pump-mixer, using pre-mixed cementitious material and additives supplied by collaborating companies. The construction site is located in a temperate-humid seasonal climate, with an annual temperature range of 5 to 25 °C and relative humidity of 70 to 90 %.

The prototype was built approximately 5 km from the University campus in Concepción (Latitude 36°46'22", Longitude 73°03'47"), on a site within a residential neighbourhood developed by the real estate company. Construction was planned in accordance with national regulations [29], which require a permit process supported by detailed design documentation and compliance with standards for habitability, universal accessibility, and seismic performance, particularly focusing on lateral stiffness as defined by NCh433-2009 and DS61-2011 [30, 31]. National legislation also specifies thermal envelope requirements for housing, and the city imposes additional regulations regarding transmittance, ventilation, and windows under an air pollution reduction plan [32]. The on-site construction sequence included marking layouts on the terrain, creating continuous foundations, and preparing reinforcements and floor bases, followed by assembly of the printed elements with integrated structural bars and concrete filling. Subsequently, the roof was constructed, installations were completed, doors, windows, fixtures, and furniture were installed, and sealing and finishing works were performed, including covering, rainwater drainage, and exterior landscaping. Architectural design alternatives were also explored using the parametric programming and additional design software, considering dimensions, surfaces, spaces, wall lengths, and formal and spatial expressions. Compliance with national housing regulations, structural and environmental standards was reviewed, and the construction outcome was documented and disseminated.

3. Results

3.1. Staff organisation and preparation

The collaboration between the University and the real estate company for the housing prototype with 3D-printed elements was formalised through an interinstitutional agreement. The real estate company appointed a local manager to coordinate activities with the University and the associated construction company. A working group was then established, comprising professionals from the collaborating companies, academics in architecture, construction engineering, and civil engineering, laboratory technicians, project staff, interns, and additional workers.

Personnel were organised into teams according to key tasks, typically combining university participants with external members. The general management team was led by a university academic alongside the real estate company's local manager, supported by a professional assistant. An architectural and structural design team maintained integration and oversaw construction tasks, including several specialised roles. In addition, there were on-site and laboratory work teams, representatives from collaborating companies, and occasional workers. This organisational structure functioned effectively; however, throughout the process it became necessary to strengthen the definition of tasks, communication channels, and information sharing due to the exceptional nature of the activity.

An initial schedule of activities was established, specifying conditions, materials, and equipment for implementation. University activities were concentrated in a prototyping laboratory with part-time support staff. The real estate company provided the site and facilitated nearby spaces for meetings, on-site work, and material storage. The initiative commenced with preliminary tests for printing walls, verifying the mixture preparation, layer thickness, stability at the required height, and hardening, as well as the size and weight for transport and installation of reinforcements, insulation, and building services.

3.2. Architectural design

The architectural design of the prototype aimed to exemplify a detached house, a housing typology common both nationally and globally. A basic form was defined to suggest alternative layouts or configurations for different sites. Given the experimental nature of the project, a minimal single-storey volume was adopted, comprising three rooms in a linear arrangement, demonstrating potential residential occupancy for one or two residents. The house was oriented with its length parallel to the main exterior street to enhance public visibility.

The design combined straight sections, common in residential construction and suitable for conventional product installation, with curved sections, which are more efficient for 3D printing due to their greater stability, speed, and expressive potential. This approach aimed to demonstrate both the adaptability of 3D-printing technology to conventional forms and its innovative capabilities. As a result, an oblong general profile was defined, with its longest axis running east–west and a total built area of 29.38 m^2, including a usable indoor area of 24.58 m^2.

The entrance and interior circulation were positioned on the side adjacent to the public street on the southern side, receiving less sunlight, while the habitable spaces faced north to maximise solar exposure. A central core was designated for sanitary equipment (bathroom and kitchen services), with the bedroom located at the eastern end and the living–dining area at the western end to take advantage of varying sunlight throughout the day. A superimposed roof with eaves and an inward-sloping cover was designed, featuring a central rainwater collection channel draining toward the west (Figure 3).

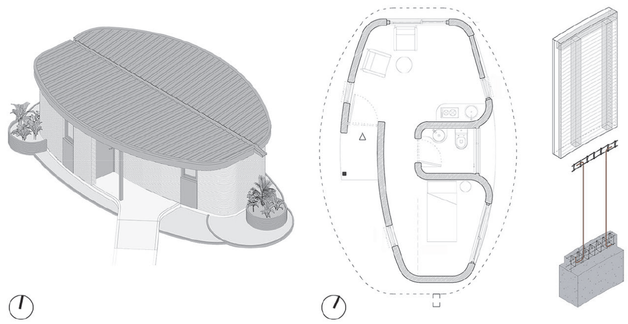

Figure 3. Architectural Design (left: aerial view; Centre: Plan, Right: Wall details)

The general layout, featuring open rooms oriented toward the sunny side, a central sanitary unit, and a recessed entrance, defined four main wall structures forming the perimeter and separating the interior spaces. Wide curves were used on the longer external walls, while the shorter and internal walls were straight with small-radius rounded corners. This arrangement provided rooms with straight sides to facilitate occupancy and furniture placement, while the curved and converging edges created a cosy envelope, producing a continuous sinuosity and a distinctive external appearance. Large full-height openings were positioned on the sunny side to maximise solar radiation, with protective eaves to reduce overheating during peak summer hours. These openings ensured constant natural illumination, with sunlight entering from varying angles throughout the day. Smaller openings were incorporated on the southern side, together with a lateral opening near the kitchen counter, to supplement lighting and enable cross-ventilation.

The roof extended over the entrance to provide rain protection. Exterior planters and paved areas were designed to enhance the outdoor environment and support outdoor activities. All these elements employed circular or curved forms that complemented the overall architectural language of the house. A wheelchair-accessible ramp and rainwater collection container were also included.

3.3. Structural design

The structural design of the prototype was developed to achieve earthquake-resistant performance in accordance with Chilean regulations. This was accomplished through the use of reinforced load-bearing walls with continuous foundations, upper connectors, and a lightweight roof to minimise vertical loads. The mechanical behaviour of the printed walls was treated as equivalent to that of confined concrete block masonry walls with internal reinforced concrete columns and beams, anchored to the foundations, following Delavar et al. [33] and the ACI 318-19 code [34]. The walls feature a double printed facing, each 4.5 cm thick, separated by a 12 cm cavity and connected every 60 cm with double sections to form a filled column measuring 20 × 20 cm and an upper beam of 20 × 30 cm. All structural elements were produced with a cementitious mixture having a compressive strength of $f_c^{'}$ ≥ 49.03 MPa and an isotropic modulus of elasticity of 3,500 MPa at 28 days.

For the foundations, columns, and upper beams, G-20 concrete with $f_c^{'}$ ≥ 19.61 MPa at 28 days and a defect fraction of 10 % was used. Foundations were reinforced with four 10 mm diameter bars, columns with a 12 mm bar, and upper beams with two 10 mm bars with transverse ties. Additional reinforcement bars were installed in anchorage zones, all fabricated from A630-420H steel.

Additionally, the installation of lintels composed of hollow square steel tubes measuring 40 × 80 × 3 mm, with a yield strength (f_y) of 264.8 MPa, was included to improve wall connectivity. The roof was designed as a metal structure made of galvanized profiles, 1 mm thick and 60 mm wide, fabricated from ASTM A 653 SQ Gr40 steel with f_y = 275.76 MPa The roof structure incorporated low-height trusses in the transverse direction and latticed beams in the longitudinal direction, both with diagonal bracing. The roof featured a double slope towards a central axis and extended eaves. At the entrance, a roof extension was supported by an additional metal column measuring 40 × 40 × 3 mm.

The analysis considered a soil with a static allowable bearing capacity of 0.098 MPa and a dynamic allowable bearing capacity of 0.127 MPa. Applied loads included self-weight (concrete: 2400 kg/m³; steel: 7850 kg/m³), a live load of 200 kg/m², wind loads, and seismic loads with an effective ground acceleration of 0.4 g. As this was a non-traditional construction system, a response reduction factor of R = 2 was adopted, in accordance with Chilean seismic design standards [33]. The most unfavourable seismic coefficient corresponded to C_{max}, with base shear and seismic weight calculated according to the standard.

The structural strength of each element was verified under the most unfavourable load combinations, including axial, shear, and bending moments. Displacement limits were checked to ensure compliance with NCh 433 and DS61 standards. Calculations were performed using the finite element software ETABS, complemented by spreadsheets in MathCAD and Microsoft Excel. It was also considered that 3D-printed concrete exhibits compressive capacities approximately 70 to 80 % of those of conventional concrete, as reported by Wolfs [35]. Based on design equations for confined and reinforced masonry (derived from TMS 402/602), a reduction factor of 0.75 was applied in the calculations for the prototype.

The structural analysis assumed that the house was founded on low-density soil with a static allowable bearing capacity of 0.098 MPa and a dynamic allowable bearing capacity of 0.127 MPa. Vertical loads included the self-weight of materials (concrete: 2400 kg/m³, steel: 7850 kg/m³) and a live load of 200 kg/m². Lateral loads accounted for both wind and seismic forces, with seismic loads governing the design. Given that the house is located in Chile's highest seismic hazard zone, effective ground accelerations of approximately 0.4 g were adopted.

As this is a non-traditional construction system, the Chilean seismic design standard NCh 433 requires a response modification factor of R = 2 and the adoption of the most conservative seismic coefficient (Cmax). Structural resistance was verified for each element under the most unfavourable load combinations, ensuring compliance with displacement limits specified by NCh 433 and DS61.

3.4. Construction planning

The printed walls were designed with hollow sections to accommodate structural reinforcements in the columns (anchored to the foundation beam) and at the upper edge, with intermediate voids for additional thermal insulation. Finishes were agreed upon with the collaborating companies and included gypsum board for ceilings, mineral wool insulation, corrugated sheets for roofing, wooden boards for eave ceilings, and wooden panel doors. Some innovative materials were also introduced, such as sprayed epoxy paint with crushed cork for wall coating (retaining the printed texture), wooden floor tiles, PVC windows with sealed double glazing, surface-mounted electrical accessories, novel sanitary and kitchen fixtures, curved wooden sheets and metal strips for roof edges, and various seals and adhesives.

To facilitate transportation, the walls were subdivided at points aligned with smaller openings, ensuring that no individual section exceeded approximately 1.5 tons in weight (Figure 4). This resulted in seven main sections. Additional smaller elements were printed, including a low wall for the external side of the bathroom and three planters. During printing, material shortages at an intermediate stage required the lengths of two wall sections (2 and 3) to be reduced.

All printable wall sections featured extended horizontal shapes with curved portions, with total lengths ranging from 0.61 to 3.58 m and widths from 0.25 to 1.46 m. The walls maintained a uniform thickness of 20 cm, with axial lengths between 0.85 and 3.76 m and a continuous height of 2.3 m. Additionally, three smaller end walls, 0.9 m high, were included to accommodate window openings.

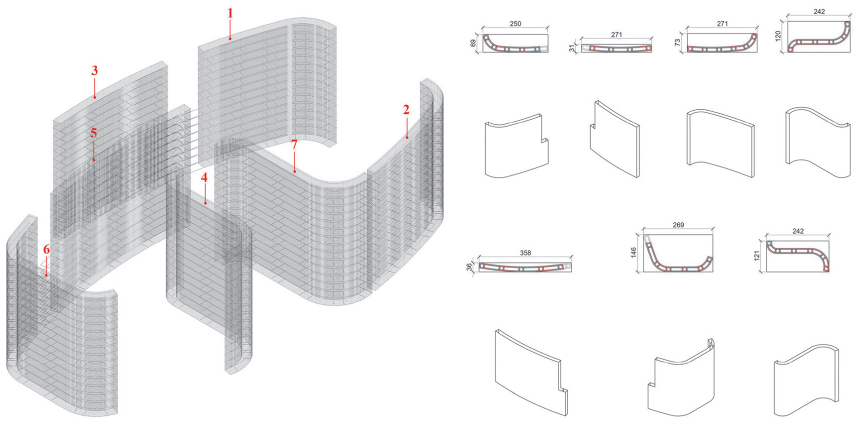

Figure 4. Walls planned for printing

3.5. Parametric programming

After defining the general design of the prototype, the shapes of the walls and smaller elements were refined using parametric programming to establish the geometric layout and generate a printing path for each piece. The horizontal layout of the longitudinal walls and corners was defined using arc chords, setting the centre positions of the radius, start points, and end points, whereas the transverse walls were positioned through an orthogonal grid of axes at parameterised distances. The overall layout was standardised with two longitudinal distances, two transverse distances, four arcs, and five angles to define the seven wall sections, incorporating 11 curvatures applied similarly in two, four, or six instances (Figure 5). More complex curvatures, height variations, and textures were not considered in the initial experimentation of larger-scale designs.

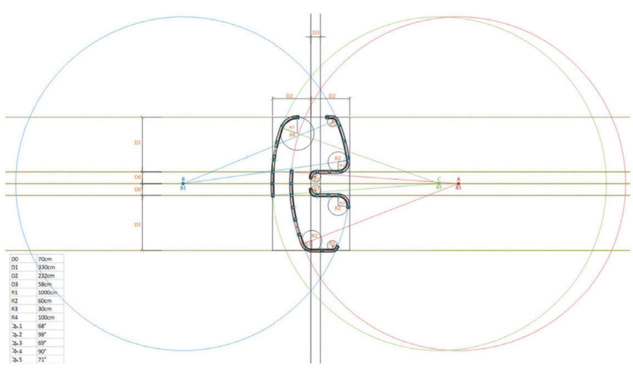

Figure 5. Parametric design of home prototype

Additionally, the parameters for the distances, radii, and angles were modified to generate various configurations, particularly larger surface areas, to test the ability of the design to accommodate different housing characteristics, particularly larger sizes. The interior distances of the rooms and the total surface areas were recorded to verify the functionality, and additional wall sections were added to create more rooms or with minor modifications. Complementary straight configurations or designs with interior courtyards were also included. Some alternatives were selected, for which complete building models and scaled 3D-printed mock-ups were made. A generative shape system was also developed, as described in a previous article [34], oriented toward the initial definition of the architectural volume.

Furthermore, the geometry of the wall sections and other elements was programmed to generate a layer-by-layer printing path, performing slicing, perimeter definition, and linking with point adjustments to generate instructions to control the printing machine in the G-code. For the double walls, staggered sections were included to accommodate columns, which were tested in printed samples to determine the path that minimised material consumption while maximising speed. The cord width was set to 4.5 cm, with a layer height of 1.5 cm, and 153 double-cord layers were required to reach the total wall height. The programming accounted for the arrangement and sequencing of walls within the printing area for each work session, which had to be adjusted based on space availability, material supply, personnel, and transportation constraints.

3.6. Wall printing

The printed walls and smaller elements were fabricated in the university laboratory using the previously described gantry printer and mixing pumps, with a partial-time team working with this machine for the first time (Figure 6). Initially, printing tests were conducted to evaluate the equipment setup, mix preparation, pumping, printing speed, and quality of execution. These tests involved printing low-height wall sections while simultaneously analysing structural and architectural design alternatives for the prototype.

Figure 6. Printing of Walls in University Lab

The seven wall sections planned for printing were produced in four batches, with an additional batch for the smaller elements, scheduled according to material availability, machine capacity, and personnel availability. The first batches were completed over three to four days each, while the final batch was completed in a single day. Between daily work sessions for a batch, the elements and printer remained in position with the programming loaded, and an adhesion seal was applied to the final layer of each piece to allow continuation later. After the third batch, a delay occurred due to waiting for the material mix, requiring adjustments to the wall design and programming, reducing some wall sections in size. Consequently, part of the living-room side wall in the prototype was replaced with a steel-frame section with wood panelling, and a support pillar was added at the entrance due to the reduction of the façade wall. The additional batch for the low-height wall and planters was executed later, concurrently with on-site construction, and completed over two daily work sessions.

Each daily session involved four operators: two professionals and two student assistants. One professional was responsible for operating the gantry printer, reviewing the programming progress, and monitoring the mix flow and delivery using camera images from the hopper and printed element. The second professional supervised mix preparation and the operation of the mixing pump, while the two assistants handled material feeding, equipment adjustments, and occasional direct inspection of the printed element.

Each printing session was preceded by preparation of the equipment and materials, as well as programming of the machine, and followed by cleaning and disassembly of accessories, each taking approximately one hour. Printer setup involved mounting the hose, adjusting the hopper, positioning the pump and materials (in bags), and performing an initial mix and pumping test up to the extrusion stage. The mix was tested using a slump table sample to verify viscosity before confirming the procedure, particularly the water flow. The first printed layers were monitored for speed, buildability, and height consistency, sometimes requiring suspension of printing to adjust velocity or water supply, followed by restarting from the beginning. The consistency of the mix in the hopper and the buildability of the printed layers were continuously monitored to regulate water flow and printing speed, taking into account variations in environmental temperature and humidity. A few partial collapses occurred in long straight segments, necessitating suspension of printing, removal of the affected sections, and resumption of the process.

The work sessions lasted between 0.83 h and 9.42 h, depending on the programmed parts and available capacities (Table 1). The total operation time for the five wall batches was 55.05 h over 12 days, including pauses and removal of sections. The speed of the extruded layers varied due to the printer motors' movement along different axes according to the programmed trajectories. As summarized in Table 1, printing speeds ranged from 5.9 cm/sec to 12.2 cm/sec, resulting in wall section speeds between 0.3 m/h and 1.2 m/h, with a total of 21.5 hours of direct printing time, with travel times between sections totalling 29 hours.

For a wall layer with a time close to the average (Table 2), printing speeds varied from 4 cm/sec in interior wall support segments (which required nozzle movement, lifting, and descent at both ends) to 16 cm/sec in straight or wide curve sections. Shorter wall ends had speeds of 6.7 cm/sec. The printed layers measured approximately 4.5 cm in width and 1.5 cm in height, with slight variations. The sessions were conducted at environment temperatures between 12 °C and 20 °C, with relative humidity levels of 70 to 80 %.

Table 1. Printing time and velocity by wall segments

Wall	Time by layer [s]	Layer lenght [cm]	Printing speed by layer [cm/s]	Total time (153 layers) [s]	Total time (153 layers) [h]	Wall length [m]	Printing speed by wall meter [m/h]
1	70.0	690.0	9.9	10710.0	3.0	2.7	0.9
2	48.0	348.0	7.3	7344.0	2.0	0.9	0.5
3	60.0	354.0	5.9	9180.0	2.6	0.8	0.3
4	77.0	936.0	12.2	11781.0	3.3	3.8	1.2
5	85.0	853.0	10.0	13005.0	3.6	3.4	0.9
6	90.0	800.0	8.9	13770.0	3.8	3.0	0.8
7	77.0	936.0	12.2	11781.0	3.3	3.8	1.2
Average	72.4	702.4	9.5	11081.6	3.1	2.6	0.8
Total		4917.0		77571.0	21.5	20.9	

Table 2. Sections in one layer of the wall 6

Section	Length [cm]	Time [s]	Printing speed	
			mm/s	cm/s
Interior	288	18	160.00	2.67
End north	20	3	66.67	1.11
Exterior	316	27	117.04	1.95
End south	20	3	66.67	1.11
Columns	156	39	40.00	0.67
TOTAL	800	90		

3.7. On-site construction

On-site construction began in parallel with the printing of walls at the University laboratory, starting with the foundations, followed by the assembly of printed walls and installation of structural reinforcements (Figure 7). Construction then proceeded with roofing, services, and additional elements, concluding with finishes and exterior work, with specific contributions from suppliers of ready-mix concrete, additives, windows, coatings, and furniture. University researchers and assistants provided documentation and supervision, while construction company workers carried out the on-site tasks, requiring slightly more effort than usual due to the curved shapes, which necessitated custom-cut plywood moulds for the foundation bases and bending of reinforcing bars.

The supply and installation of the printed elements required clearing adjacent areas for crane-truck delivery and aligning the elements with the vertical reinforcement bars fixed in the foundations. A bonding bridge was applied to connect them to the concrete foundations, with continuous checks of levels and alignment. Contrary to initial expectations, temporary structures and additional personnel were minimally required. The provision and pouring of concrete for foundations, columns, and beams were handled by an external supplier using pre-mixed concrete. The planned thermal insulation, initially intended to be injected into the walls, was modified to polystyrene spheres to ensure continuous filling.

The roof structure and coverings consisted of multiple prefabricated pieces of varying sizes to complete the overall ovoid profile, featuring a double upper slope and lower recess, as well as connecting joists for openings and access points. These components were manufactured in an adjacent workshop and installed on-site, resulting in accurately executed inclined surfaces and curved edges.

The installation of electrical networks, plumbing fixtures, and monitoring accessories required precise coordination between different practitioners and the contractor. Some elements were surface-mounted, while others were embedded with specialised seals. The installation of doors and windows required particular attention due to the irregular edges. Wall coatings were applied in multiple layers and colours, necessitating careful planning and protection of elements to ensure proper sequencing. Ceiling and floor finishes also required additional effort to accommodate curved edges. Furthermore, the construction included access pavements, terraces, and landscaped areas with rounded edges.

On-site work was conducted over 38 days spread across six months, with daily durations ranging from approximately 2 h to 8 h, involving 2 to 6 workers per session. The total work time was 181 h, equivalent to 22.5 continuous days, or roughly 5 weeks. The project generated minimal waste, required few accessories and support structures, and maintained a zero-accident record.

Figure 7. Mounting of 3d-printed Walls on-site (left) and execution of foundations and roofing (right)

3.8. Analysis of features and processes

3.8.1. Regulatory compliance

The 3D-printed prototype was designed to comply with local regulations for construction and public occupancy (Art. 4.1.10 in [29]). Complete architectural and structural design documentation was submitted and reviewed by the technical unit of the local municipality, which granted approval. The proposed built area and height are below the maximum limits established by urban zoning, and the estimated occupancy is appropriate. Additionally, the interior height meets the minimum requirement, window dimensions comply with the established conditions, and wall materials achieve the specified acoustic reduction. Accessibility requirements for individuals with disabilities and elderly users were satisfied through the inclusion of an entrance ramp, adequately wide doors, and appropriately sized interior spaces.

To achieve permanent habitability, the construction must also comply with thermal requirements according to the climatic zone and the city's special decontamination plan [32]. The roof was designed with 100 mm of mineral wool insulation, a gypsum board ceiling, and a wood-and-metal sheet, achieving an estimated thermal transmittance of 0.33 W/m²K, in compliance with both standard and special regulations (maximum 0.38 W/m²K and 0.33 W/m²K, respectively). The walls have a weighted thermal transmittance of 0.645 W/m²K, considering reinforced concrete sections and voids filled with polystyrene spheres, sandwiched between 4.5 cm concrete layers. The upper portion of the walls is clad with gypsum board, ensuring compliance with standard regulations and approaching special requirements (maximum 1.7 W/m²K and 0.60 W/m²K, respectively).

The windows are fitted with hermetically sealed double glazing, with a transmittance of 2.9 W/m²K and a weighted surface area distribution per side of 29.4 %, 0 %, 37 %, and 6 %, meeting the standard requirement of a maximum of 2.4 W/m²K for 60 % of the window area. Special regulations limiting the maximum window area per façade to 78 %, 51 %, 38 %, and 30 % are also satisfied. The continuous concrete flooring over the ground base is not subject to specific thermal regulations. The exposed foundations do not include additional insulation, complying with standard regulations, although the special regulation requires a minimum R-value of 45 R100.

The special environmental plan additionally mandates condensation risk control, addressed through water-repellent membranes on the roof and walls. Air infiltration and airtightness requirements for doors and windows are met via mortar and silicone seals at all junctions, complemented by overlapping panel designs around openings.

3.8.2. Environmental performance

The computational simulation of energy performance indicated an average annual demand of 2,228.8 kWh/year for the entire house, equivalent to 79.6 kWh/m²/year, distributed between heating and cooling according to the season. The highest cooling demand occurred in February (250 kWh), while the highest heating demand was in August (160 kWh). The total annual energy demand was estimated at 2,240 kWh/year, which, based on the national electricity tariff, corresponds to approximately 448 USD per year. This represents less than half the national average per household and is around 20 % lower when normalised by equivalent surface area.

Environmental monitoring is being conducted using four indoor sensors measuring temperature, humidity, and CO_2, together with an outdoor weather station. A controlled thermal regime monitoring phase will follow, employing a 12,000 BTU/h HVAC system, with sensor data collection, air infiltration measurement (blower door test), surface transmittance analysis, and thermographic imaging. Initial measurements over a two-week summer period, under free oscillation conditions (without climate control), recorded an average indoor temperature of 23°C, with daily highs of 27 to 29°C in the afternoons and lows of 17 to 18°C at dawn. Relative humidity, inversely correlated with temperature, averaged 51 to 53 %, with maximum values of 61 to 63 % and minimum values of 34 to 9 %. CO_2 levels averaged 415 to 432 ppm, with peaks of 493 to 597 ppm and minima of 361–376 ppm.

According to ASHRAE 55 comfort temperature ranges, thermal comfort is achieved in winter with average temperatures of 20 to 24°C and in summer with 23 to 26°C, with relative humidity between 30 % and 60 %. The prototype maintained these comfort conditions 48.21 % of the time, exceeding national records for comparable homes. For indoor CO_2 levels, ASHRAE 62.1 defines an optimal range

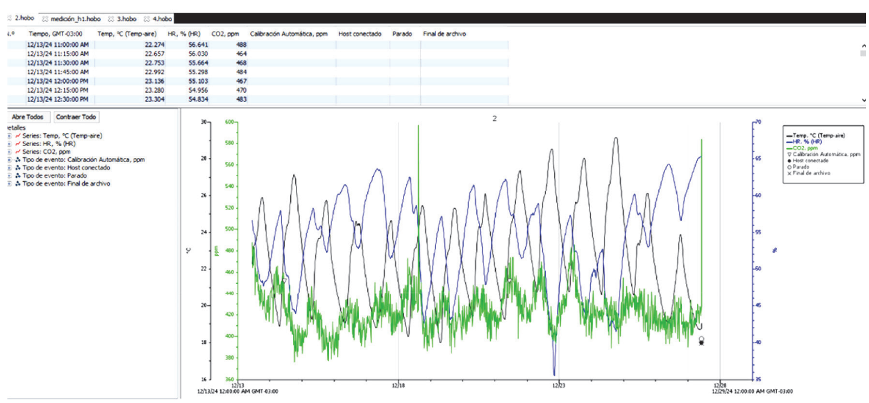

Figure 8. Environmental monitoring in living room for 14 days during summer

of 400–800 ppm, while the World Health Organization considers levels below 1,000 ppm as healthy (Figure 8). These results indicate that the house can provide both thermal and indoor air comfort without additional climate control.

3.8.3. Structural analysis

The structural analysis confirmed that the proposed model adequately resists the applied loads, with stresses transmitted to the ground remaining below allowable limits. Seismic deformations (drift in X and Y directions) were within the permissible ranges established by current regulations. All structural elements met the calculated resistance requirements, ensuring the serviceability and safety of the house. The walls, for instance, passed the maximum compression and shear resistance tests. Furthermore, the performance of lintels, tension anchors, shear anchors, foundation concrete pull-out, foundation anchor slip resistance, wall pull-out, and lateral detachment was satisfactorily verified. However, the sliding resistance of the wall anchors and the tension anchors, although compliant, exhibited narrow safety margins relative to regulatory limits.

A finite element analysis performed using ETABS software confirmed that ground stress levels remained below acceptable thresholds and that seismic deformations conformed to Chilean regulations. Overall, the structural elements demonstrated adequate resistance, ensuring the long-term safety of the prototype. Complementary experimental tests are planned to further refine and validate these numerical calculations.

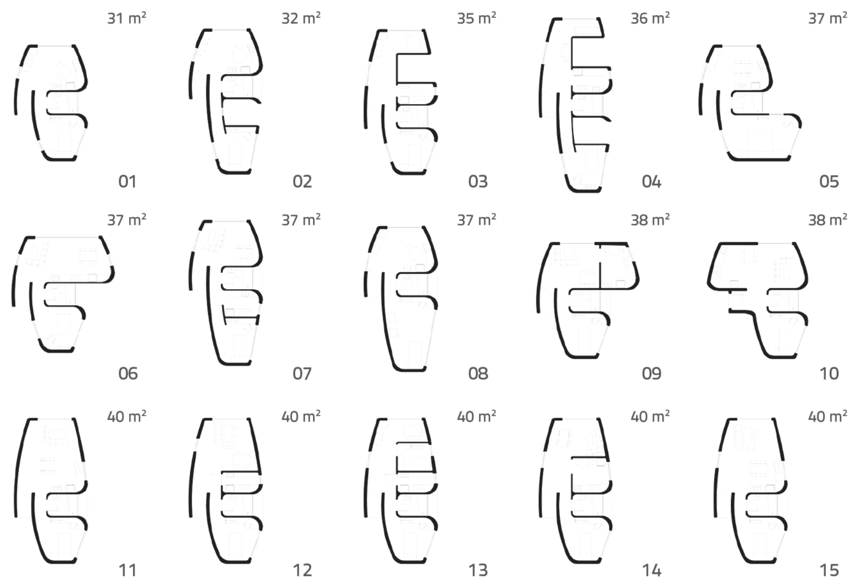

Figure 9. Architectural variations in home designs

3.8.4. Architectural variations

Parametric programming enabled the exploration of over one hundred single-story housing layouts, ranging from prototypes of similar size (30 m² with one bedroom) to homes larger than the national average (90 m² with three bedrooms). Interior room dimensions were recorded to verify adequate occupancy. Design adjustments involved longitudinal or transverse expansions while maintaining a central sanitary core, which occasionally accommodated two bathrooms, and a central entrance. Some models incorporated intermediate recesses, such as interior courtyards, duplicated profiles, or centrally located bathrooms to ensure windows in all habitable rooms. Compact and extended configurations were developed, alongside staggered, L-shaped, and U-shaped designs. Challenges were noted regarding furniture placement, particularly along curved walls, room separations, and larger openings that posed structural constraints. Multi-level designs (two or three stories) were considered feasible with appropriately designed seismic-resistant mezzanines and staircases.

Five detailed models were developed that fit within the width of the 3D printer, ensuring on-site constructability. These designs featured floor areas of 24.5, 37, 46, 64, and 84 m², with one to three bedrooms, and some included separate kitchens (Figure 9). The original layout was preserved while adjusting axis distances, central positions, and curvature radii, and adding up to three interior walls. This demonstrated the versatility and effectiveness of parametric programming in generating valid design variations.

3.8.5. Construction process

The execution of the prototype proceeded according to the established plan and available resources, with occasional extensions due to intermittent work and specific material requirements. The technical development and coordination were more demanding than usual because of the experimental nature of the project, with some tasks proving particularly challenging. During roundtable discussions with researchers and professionals, four potential improvements were identified to enhance productivity, sustainability, and architectural diversity:

- Improved project scheduling, particularly regarding the provision of materials, personnel, equipment, and necessary adjustments, to accelerate overall execution through the printing of elements.
- Adaptation of structural reinforcements, seals, and installations to accommodate the curved shapes and rough finishes of the printed elements.

Figure 10. Photographs of executed prototype

- Verification of measurements, levels, and plumb lines of printed components to ensure proper integration with subsequent elements.
- Optimisation of additional elements, such as roofs and fixed furniture, to enhance the efficiency of the printing process.

The prototype was completed, including services, furnishings, and exterior elements, along with informational signs and photographs documenting the construction process (Figure 10). A public opening was held, attended by guests from the local construction industry and academia. Open visits are now held every two weeks, with registration and guidance provided by a member of the research team. Over four months of exhibition, the prototype has received nearly 300 in-person visitors, primarily professionals and students, and has generated a dozen press releases, including several international, reaching over 300,000 direct contacts with approximately 1,000 reactions or comments. Visitors appreciated the unique shape and finishes, the perceived structural stability, and the climatic adaptation to sunlight and rainfall, with particular attention to the interior spaces. Feedback highlighted the novelty of the architectural design, alongside concerns regarding costs, seismic and thermal performance, and potential employment implications associated with the adoption of this technology.

4. Discussion

The prototype experience is inherently limited to the specific case and its contextual conditions; consequently, the outcomes may only be partially applicable to other scenarios. The design decisions, available resources, and activities undertaken-including the records maintained-represent analytical constraints. Despite this specificity, several lessons have emerged from applying novel technologies to conventional design and construction practices, highlighting aspects that could inform future 3D-printed constructions. Furthermore, several anticipated outcomes require verification to support projected expectations.

The building's features, residential potential, and strategies for structural and environmental performance were developed and implemented, but they necessitate experimental evaluation over time [36]. The successful execution of the construction process, utilising printed elements to realise this prototype, represents a significant achievement that demonstrates potential dwelling possibilities. However, the functional performance and long-term effectiveness remain to be fully assessed. The adaptation of various construction tasks and materials also indicates the potential for integrating 3D-printing technology into broader building development, both within Chile and in similar contexts. Moreover, the ability to monitor the behaviour of a 3D-printed structure, combined with public engagement and recognition, holds significant potential for advancing the adoption and wider application of this technology.

This prototyping experience, as documented in this article, provides detailed reference material for the field, which has often been limited to general reviews or reports on specific tasks without comprehensive accounts of the construction process. The demonstrated possibilities for architectural diversification, earthquake-resistant configurations, and climate adaptation offer specific contributions to housing development in earthquake-prone regions and challenging climates using new technologies.

Within the broader context of residential construction in Chile, and in the global experimentation with 3D-printed homes, this work presents a concrete practice that advances both technical capabilities and social projections. Implementing the proposed strategies and verifying their performance is a crucial step towards consolidating this technological capacity.

5. Conclusion

The development of this prototype represents a multidisciplinary endeavour that advances the application of 3D-printed construction by demonstrating its design and execution to expand residential possibilities. An architectural framework for a basic design and multiple housing configurations is presented, reflecting compliance with local regulations and the potential of 3D-printed construction. Thermal performance is assessed through standards-based analysis, simulations, and initial monitoring. A structural strategy for seismic zones is also outlined, with both theoretical evaluation and physical verification. A comprehensive construction process is described, including a review of activities and public dissemination. This detailed documentation and analysis are unprecedented in the emerging literature on 3D-printed construction [6], providing insights to expand capabilities and clarify associated challenges. The proposed architectural design, combining straight and curved forms, presents a novel and adaptable formal repertoire that integrates structural and environmental considerations while achieving positive public reception. Structural monitoring validates earthquake-resistant performance, supporting the development of resilient housing solutions. The adaptation of 3D-printed homes to varying climatic conditions further facilitates improvements in energy efficiency, environmental comfort, and sustainability. Moreover, the inclusion of variable layouts demonstrates the potential for diverse housing models. This experience is relevant for promoting the broader adoption of 3D-printed homes across different geographical contexts and demographic segments. However, challenges remain regarding suitability and performance. 3D-printed construction has shown considerable promise in recent years and must progress toward productive, scalable applications. Detailed reporting of these advances is essential to guide the ongoing development and implementation of 3D-printed housing solutions.

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