Assembly of Stay-In-Place Concrete Blocks Using a Robot

R García¹, A Perez², J A Pulido², P Ulloa³, E Forcael³

¹Depto. Arquitectura. Universidad del Bio-Bio, Concepción, Chile.
²Depto. Ciencias de la Construcción, Universidad del Bio-Bio, Concepción, Chile.
³Depto. Ing. Civil y Ambiental. Universidad del Bio-Bio, Concepción, Chile.

E-mail: rgarcia@ubiobio.cl

Abstract. This work presents an experiment where a constructive system with hollow blocks is assembled using a robot. These blocks form a stay-in-place support to receive a mixture onsite, generating a monolithic concrete wall with vertical steel reinforcements, as well as providing thermal and acoustic insulation capabilities. The assembly system is tested with an industrial robotic arm, programmed to assemble the blocks following the layout of a building. The tests demonstrate the technical feasibility for execution onsite, with productivity advantages and suitable finishes. Thermal and acoustic performance tests have also been carried out to determine the fillings and structural studies for the complete building layout, along with digital modelling of the design and construction management. The assembly tests have shown the speed and versatility of the robotic system, although the planning and installation of the equipment considering the building as a whole must be developed further.

1. Introduction

Construction is one of the most important sectors in the economy. In Chile, it represents around 8% of the GDP and employment, with some 3,000 companies [1]. This sector contributes around half the country’s entire investment, with a third alone destined to buildings (US$10 billion/year) [2]. According to the National Strategic Program (PEN in Spanish) for Sustainable Construction and Productivity – Construye 2025, the sector needs to increase its productivity, making buildings more expensive and affecting the economy and social development. This is due to three main factors:

- The lack of coordination and planning.
- The limited standardization and industrialized prefabrication.
- The shortage of qualified labor.

In Chile, due to its seismic nature, the prefabrication of elements is complicated, as these must be integrated into dynamic structural systems. As a result, most medium-height buildings are built using reinforced concrete walls accompanied by insulated cladding to improve their thermal behavior [3]. There are currently projects along these lines, like the mandate-law of the General Ordinance of Urbanism and Construction (Art. 4.1.10), the Standardized Terms of Reference (TDRe) or the Sustainable Construction Standards for Housing (ECSV), which are all voluntary, but nonetheless demonstrate an increase in the demands.

The construction industry in Chile is currently evolving into an ever more regulated setting, looking to guarantee quality and safety in construction, as well as consider seismic, energy efficiency, environmental and consumer protection requirements. The demographic and economic growth
Meanwhile, is also generating growing infrastructure demands, which need to be handled in shorter timeframes and at more affordable prices. This situation is forcing incorporating quicker and more efficient techniques to reduce project timeframes and costs.

Sustainable construction is encouraging new construction systems that improve productivity and lessen the adverse effects the industry has on the environment [4]. There is a growing acknowledgment about the importance of prefabrication to improve productivity and its reduced impact on ecosystems [5], mainly as a result of less construction waste [6], the improvement of quality control [7], less noise and dust during onsite work [8], higher standards being reached [8, 9], savings in costs and time [10], less labor [11], and a reduced exhaustion of natural resources [12, 13]. Therefore, sustainable construction, at an international level, is associated with construction systems that improve productivity and reduce the impacts the construction industry has on the environment [14]. Prefabrication is shown as being one way to link both of these goals [10]. However, generating prefabricated solutions for walls in Chile has important limitations when it comes to guaranteeing a good performance during seismic events, with reinforced concrete structures built onsite having a better performance when facing this risk [15].

Stay-in-place (SINP) formworks look to generate elements that hold the poured concrete and form a permanent part of the building, as a cladding, looking to reduce materials, labor and use the resources more efficiently. They can also provide protection, a better-quality finish and even contribute structurally to the hardened concrete. These formwork elements are light, easy to place and can, in some cases, help remove the need for structural element reinforcements [16]. However, some authors identify that retraining the labor force is necessary as the concreting and prefabrication processes require specialist skills [10]. For this reason, implementing prefabricated construction systems through automated equipment used in other industries can help overcome these limitations.

Robotics have started to be used in different industrial sectors, providing important production advantages, although with resulting labor and social transformations [17]. In construction, the incorporation of robotic equipment is still at a fledging stage. This is due to the complexity of the tasks involved, which also tend to be done on different sites for short periods of time [18]. In recent times, the development of large-scale printing technologies using robotic arms has encouraged the application of automated equipment in construction. This has led to applications in other associated worksites and inspired new perspectives in the architectonic design of buildings [19, 20] considering, in particular, the capacity of linking the digital modeling of buildings (BIM systems) with construction management, becoming a continuous design and execution process in versatile and accurate IT platforms [21, 22].

In particular, the handling of elements with robotic systems has been extensively considered in logistics applications, developing specific fastening and transportation procedures for given production units [23, 24]. Its implementation is also suggested in industrialized construction processes, although there are limited experiences to date. The application of robotic systems in construction requires a regularity of the actions and elements involved, with programmable variations that consider the execution capacities of the respective equipment. Thus, it requires a combination of the constructive and automation conditions, which have specific challenges and a broad potential. This work plans to check the execution of some assembly tasks in a stay-in-place block construction system that synthetizes construction actions, guaranteeing their environmental and structural performance. This, with the goal of considering the possibilities of general automation for the execution process of an industrialized construction strategy.

2. Development of the Stay-in-place Construction System

2.1. General formulation of the blocks
The proposed system is a prefabricated block for framing concrete walls onsite, which is left to provide the role of a superficial finish as well as to increase the thermal characteristics of conventional concrete cladding. The block comprises a metal structure within two surfaces with a reduced conductivity. The thickness of this surface varies depending on the thermal transmittance required where it is being used.
These surfaces are formed by lightweight mortar which includes low thermal conductivity aggregates (expanded perlite and expanded polystyrene perlite) and an aerator additive to improve their rainwater tightness and permeability to steam, to avoid condensation inside the building (See Fig. 1).

![Figure 1. Block prototype. Source: own preparation.](image)

Another design factor of the element is related to its size and weight to make its assembly, transportation and placement easier and safer [14]. For this reason, the block is 120 cm long by 40 cm high (the thickness varies depending on the wall and thermal area), so the use of lightweight mortar means that its weight is less than 50 kg per unit (which allows it to be moved using a Kuka KR120 R2500 robot whose loading limit is 120 kg).

The manufacturing is done in seven stages using modulated molds and a vibrating table to compact the mortar of the surfaces. The first step involves assembling the mesh which provides stability to the block’s faces, as well as to bear the pressure of the concreting onsite. The execution of the block is done in two phases, where the faces can have a different composition (See Fig. 2).

![Figure 2. Manufacturing of block prototype. Source: own preparation.](image)

2.2. Description of the construction system
The block allows building concrete walls without a height limitation given that the concrete poured inside forms a structural element to face loads and seismic events. Thus, the prefabrication increases productivity through the “Stay-in-place” system that provides the surface finish and the thermal insulation, eliminating the times of additional elements. It also provides a higher quality for the surfaces and hygrothermal requirements (Fig. 3). Traditional formworks, which are more than half the cost of a concrete element implemented onsite, are replaced [25]. The main differences versus the conventional concrete walls or block methods are:

- The whole system takes less time as it integrates surface finish, thermal insulation, etc., and removes the supports or the stripping of the formwork.
- It considers a lower cost on using less materials and labor.
• The prefabrication of surfaces improves the quality of the finish and the hygrothermal performance, eliminating leaks due to poorly built walls.

• Lower environmental load, as it is not necessary to install cladding, and in the prefabrication process, natural aggregates and additives with a low environmental load are used. The system is also 100% recyclable.

As a result, the solution is innovative from a productivity point of view, and also when considering sustainability. The innovation in productivity is associated to lower building times, fewer materials and, consequently, a lower cost. Innovation, from the sustainability side, is related to reducing the environmental load of sites, the use of natural materials for lightweight concrete and a higher recyclability of the system, as well as a reduction in its energy demand and CO2eq emissions, in both the construction and use phases.

![Figure 3. Execution of the concrete wall using “Stay-in-place” prefabricated blocks. Source: own preparation.](image)

3. **Robotic Assembly Experiment**

3.1. **General Conditions**

The experiment in the assembly of the stay-in-place block construction system using a robotic arm was done using a Kuka KR120 R2500 robot installed on a fixed base inside the University of Bio-Bio’s concrete laboratory (Concepción, Chile). This piece of equipment considered a robotic arm with six degrees of freedom [26], that can handle 120 kilos of load and has a 2.5m radius. It is set up with a 7m long rail in a new installation. It was also run with BIM modeling, using Autodesk’s Revit software, making architectonic examples with the construction system, including hollows, cover, foundations and different types of blocks (Fig. 4). On the other hand, the Robot’s control programming was done using
the Kuka-PRC plug-in in Grasshopper-Rhino. This same capacity is available for the internal language in Revit (Dynamo PRC), which allows integration with the BIM platform.

![Conceptual Image of the Assembly using the Robotic Arm](image)

**Figure 4.** Conceptual Image of the Assembly using the Robotic Arm. Source: own preparation.

3.2. **Planning the Assembly**
Initially, an assembly sequence was planned using the general layout of the building’s walls and the radial-linear scope of the robot. The positions of the axis and/or the fixed positions of the robotic arm were set on the foundation’s and successive level’s floorplan, distributing the work segments. Then, the horizontal sequences within the segment and the location of the pile of blocks for assembly were set in the robot’s lateral scope area.

3.3. **Route programming**
A parametric programming of the arm’s route is applied in the work segments to transfer, in vertical series, each block from the pile to its consecutive position in the sequence. Then, a pick-up and delivery programming was carried out in each pick-up and delivery point, respectively. Each programming series is repeatable and adaptable to the different geometric positions considering the reference levels.

3.4. **Preparation of the Holding Claws**
A special work tool was prepared to hold the block. This was based on the rock claw model, which would allow lifting and delivering in each position. This claw was made from a 15 mm tilted sheet, with CNC cut and bolts, including an automatic brace.

3.5. **Holding and Placement Tests.**
The robotic arm assembly experiment was performed under laboratory conditions (Fig. 5) with test blocks and video recording to account for times and observations of the process. This was done using the holding claws, stockpile positions and block placement following the distances estimated in the BIM model to reproduce the system’s execution procedures.
3.6. Test results

The tests run considered initial programming and setup processes, checking the work positions and then holding, lifting, transferring and delivery sessions in the different positions (Fig. 6). The displacement speed was regulated at 5m/second, to minimize the arrival oscillation, and the experiments were done with a delivery distance of 2.5m, considering the work space mean (5m radius). The operation times reached in tests with a suitable holding and delivery accuracy were the following (Table 1).

| Table 1. Assembly Tests |
|-------------------------|
|                        |
| Duration (seconds)      |
| Holding | Lifting | Transfer | Lowering | Delivery | Total |
| 5        | 5       | 30       | 10       | 5        | 55    |

The magnitudes and execution reached, with a total per block of approximately 50 seconds (depending on the delivery height), were approximately 25% of the manual work time and allow estimating a duration of less than one hour to place 50 blocks, corresponding to 9 linear meters of wall which is the operational scope of the robot in a fixed position for an equivalent stockpile. This suggests a high advance in productivity with the installation of the system, as well as the integration of cladding.
On the other hand, the robot’s programming allows guaranteeing the flexibility of delivery in different setups informed by the BIM model following the positions of the equipment onsite, providing, in this way, a digital management system linking the design and the execution.

4. Conclusions
The stay-in-place concrete block execution tests have shown the technical viability of the production of these construction elements in suitable sizes for the assembly and execution of buildings, with suitable finishes and affordable costs. In addition, thermal and acoustic performance tests have been run to determine the structure studies and refills for the building’s complete process, which demonstrate their suitability to local regulations. The assembly tests have shown the speed and versatility of the robotic system, although the procedures for sequences and diversity of pieces must be completed, as well as the planning of the block stockpiling positions and the installation of the equipment versus the whole building.

In this way, the development of the construction system and the assembly experiment with a robotic arm express a potential support for building processes, regarding productivity and execution quality, in terms of possibilities to improve speed, flexibility and accuracy of tasks, as well as guaranteeing interior environmental performance. This system does consider an important investment in production systematization and equipment, as well as labor changes which would clearly affect the sector’s organization. However, it is necessary to address new building perspectives to face the environmental and productive challenges.

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References
[1] Macroeconomía y Construcción, I. 2014. Informe MCCh No 41. Dec. 2014. Retrieved from http://www.cchc.cl/uploads/archivos/archivos/MACh-41.pdf
[2] CORFO 2015 Productividad y Construcción Sustentable. Retrieved from http://www.agendaproductividad.cl/wp-content/uploads/sites/22/2014/10/PPT_Programa_Estrategico_Construccion_Sustentable.pdf
[3] Instituto Nacional de Estadísticas 2014 Anuarios INE. Santiago de Chile.
[4] Li, Z., Shen, G. Q., & Xue, X. 2014. Critical review of the research on the management of prefabricated construction. Habitat International, 43, 240–249. https://doi.org/10.1016/j.habitatint.2014.04.001
[5] Tang, L., Shen, Q., & Cheng, E. W. L. 2010. A review of studies on Public–Private Partnership projects in the construction industry. International Journal of Project Management, 28(7), 683–694. https://doi.org/10.1016/j.ijproman.2009.11.009
[6] Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S., & Wong, I. 2008. Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings. Automation in Construction, 17(3), 333–341. https://doi.org/10.1016/j.autcon.2007.05.013
[7] Jaillon, L., & Poon, C.-S. 2008 Sustainable construction aspects of using prefabrication in dense urban environment: a Hong Kong case study. Construction Management and Economics, 26(9), 953–966.
[8] Pons, O., & Wadel, G. 2011 Environmental impacts of prefabricated school buildings in Catalonia. Habitat International, 35(4), 553–563. https://doi.org/10.1016/j.habitatint.2011.03.005
[9] López-Mesa, B., Pitarch, Á., Tomás, A., & Gallego, T. 2009. Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors. Building and Environment, 44(4), 699–712. https://doi.org/10.1016/j.buildenv.2008.05.017
[10] Chiang, Y.-H., Hon-Wan Chan, E., & Ka-Leung Lok, L. 2006 Prefabrication and barriers to entry—a case study of public housing and institutional buildings in Hong Kong. *Habitat International*, 30(3), 482–499. https://doi.org/10.1016/j.habitatint.2004.12.004

[11] Nadim, W., & Goulding, J. S. 2010 Offsite production in the UK: the way forward? A UK construction industry perspective. *Construction Innovation*, 10(2), 181–202.

[12] Aye, L., Ngo, T., Crawford, R. H., Gammampila, R., & Mendis, P. 2012. Life cycle greenhouse gas emissions and energy analysis of prefabricated reusable building modules. *Energy and Buildings*, 47, 159–168. https://doi.org/10.1016/j.enbuild.2011.11.049

[13] Won, I., Na, Y., Kim, J. T., & Kim, S. 2013 Energy-efficient algorithms of the steam curing for the in situ production of precast concrete members. *Energy and Buildings*, 64, 275–284.

[14] Li, H., Guo, H. L., Skitmore, M., Huang, T., Chan, K. Y. N., & Chan, G. 2011 Rethinking prefabricated construction management using the VP-based IKEA model in Hong Kong. *Construction Management and Economics*, 29(3), 233–245.

[15] Luis G. Mejia, Juan C. Ortiz R., L. I. O. G. 2004. *HOUSING REPORT Concrete Shear Wall Buildings*. In E. E. R. I. (EERI) And & I. A. for E. E. (IAEE) (Eds.), *World Housing Encyclopaedia* 1–16

[16] De Sutter, S., Remy, O., Tysmans, T., & Wastiels, J. 2014. Development and experimental validation of a lightweight Stay-in-Place composite formwork for concrete beams. *Construction and Building Materials*, 63, 33–39. https://doi.org/10.1016/j.conbuildmat.2014.03.032

[17] Bock, T. 2015 Construction Robotics enabling Innovative Disruption and Social Supportability, 2015 *Proceedings of the 32st ISARC*, Oulu, Finland

[18] Gambao, E., & Balaguer, C. 2002. Robotics and automation in construction. *IEEE Robotics and Automation Magazine* (Vol. 9).

[19] Lim S., Buswell R.A., Valentine P.J., Piker D., Austin S.A., De Kestelier X. 2016, Modelling curved-layered printing paths for fabricating large-scale construction components, *Addit. Manuf.*, 12, pp. 216–230

[20] Sousa J.P. 2017, Robotic Technologies for Non-Standard Design and Construction in Architecture, *Nexus Network Journal*, 19-1, pp 73–83

[21] Davtalab O., Kazemian A., Khoshnevis B 2018 Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting, *Autom. Constr.* 89, pp. 13–23

[22] Piroozfar P, Eric R. P. Farr, Lars Hvam, Dexter Robinson, Sara Shafiee 2019) Configuration platform for customisation of design, manufacturing and assembly processes of building façade systems: A building information modelling perspective, *Automation in Construction*, 106, October 2019, Article 102914

[23] Lewis F.L., Abdallah C.T., Dawson D.M. 2003 *Robot Manipulator Control: Theory and Practice*, CRC Press.

[24] Barros T. T. and Fetter Lages W., 2014 A Mobile Manipulator Controller Implemented in the Robot Operating System, *ISR/Robotik 2014; 41st International Symposium on Robotics*, Munich, pp. 1-8.

[25] Robert, H. (2007). Think formwork–reduce cost. *Structure Magazine*, 14.

[26] International Organization for Standardization (2012) *ISO 8373:2012 Robots and robotic devices — Vocabulary, International Organization for Standardization, London*