AN INTEGRATED DESIGN PROCESS OF LOW-COST HOUSING IN CHILE

Maureen Trebilcock-Kelly,[1] Gerardo Saelzer-Fica,[2] and Ariel Bobadilla-Moreno[3]

ABSTRACT

This paper discusses the application of Integrated Design Process for the design of low-cost housing in Chile. It aims to question common practice for the development of housing based on prescriptive regulations and non-interdisciplinary work, which has resulted in poor quality building requirements. The first stage consisted in defining performance requirements for aspects such as energy demand, U value, air tightness and indoor air quality for a specific case of low-cost houses located in the city of Temuco. An integrated design process was carried out by an interdisciplinary team of professionals specialized in each of the performance aspects that were taken into account. The construction and post-occupancy stages were characterized by verifying the performance requirements, which resulted in a low-cost house prototype that included strategies for energy efficiency and a healthy indoor environment.

KEYWORDS

Integrated Design Process, low-cost housing, performance requirements, interdisciplinary work

INTRODUCTION

The concept of Integrated Design Process (IDP) has been defined by IEA Task 23 (Löhnert et al. 2003) as a procedure that aims at optimizing the building as a complete system during its life cycle through interdisciplinary work from the beginning of the design process. A similar definition by Busby et al. (2007) and Trebilcock (2009) highlights that this approach seeks to achieve high performance in a wide variety of environmental objectives by using a collaborative, multidisciplinary team whose members make decisions together based on a shared vision and a holistic understanding of the project. This study clearly shows the differences between a traditional linear methodology and an integrated design approach based on interdisciplinary collaborative work between different experts from the early stages of the process, which represents a key element in the pursuit of sustainable buildings. More recently, the concept of Performance Integrated Design (PID) has been used to define an integrated process that is performance-oriented, with an emphasis on methods, tools and procedures established to achieve clearly-defined performance objectives. A number of experiences have shown that this

1. Dept. Diseño y Teoría de la Arquitectura, Universidad del Bío-Bío, mtrebilc@ubiobio.cl
2. Dept. Diseño y Teoría de la Arquitectura, Universidad del Bío-Bío, gsaelzer@ubiobio.cl
3. Centro de Investigación en Tecnologías de la Construcción CITEC UBB, Universidad del Bío-Bío, abobadil@ubiobio.cl

process has been successful in achieving sustainable, high-performance buildings (Azarbayjani et al., 2012; Thibaudeau, 2008; Peng et al., 2015).

An Integrated Design Process should start with the clear definition of the performance indicators and requirements that will be pursued in order to orient the integrated process. In Chile, current regulations for the energy and environmental performance of dwellings are limited to the definition of U value for some elements of the envelope (MINVU, 2006). However, there are no performance requirements in terms of air tightness, indoor air quality, thermal comfort or overall energy performance. Nevertheless, important advances have been made in the energy rating of housing and with numerous design guides that direct the development of new buildings, although they are not yet mandatory.

Therefore, implementing IDP in the development of housing projects is not only important in relation to the benefits from facilitating interdisciplinary and collaborative work. It can also help to define the performance requirements, which can be verified during the process of design, construction, and dwelling use, with the general aim of improving the quality of the housing stock and thus the quality of life of users.

This paper reviews the Integrated Design Process of a low-cost house prototype in south-central Chile. It is hoped that the results obtained transcend this particular experience and yield conclusions that change current methodologies, regulations and performance requirements for the development of future low-cost housing in the country. The article also discusses the barriers faced and future challenges in this area.

CASE STUDY

The case study consists of low-cost houses in Temuco, a city located in the south-central area of Chile at latitude 39° S. Temuco has a temperate climate, classified as Cfb according to the Koppen-Geiger climate classification. Its average annual temperature is 11°C, while the warmest month—January—has an average temperature of 16°C, and the coldest month—July—has an average temperature of 7°C. In recent years, this city has experienced numerous episodes of acute environmental pollution due to the combustion of firewood for heating, and thus was declared to be a zone saturated by PM_{10} airborne pollution in 2005 and $PM_{2.5}$ in 2013 (Cortes and Ridley, 2013). Therefore, the Araucanía Regional Housing and Urban Planning Service (SERVIU) mandated the development of a proposal for low-cost housing with an innovative design and construction methodology based on an integrated approach, in order to achieve higher performance outcomes than with the practices traditionally used with this building typology.

Low-cost housing in Chile is based on a subsidy system administered by the SERVIU. Individuals in the lowest fifth of the socio-economic spectrum, known as the "at-risk" group, are entitled to a full subsidy. This makes it possible for them to afford a house worth approximately USD $20,000. While those in the second-lowest fifth, known as the "emergent" group, receive a subsidy that complements their savings in order to be able to purchase a house of higher value, usually between USD $27,000 and USD $45,000.

For this project, a single-family timber house prototype was commissioned for the emergent socio-economic group. In the first stage of the design process the building site was not clear, so the challenge was to develop the unit, while also working on a proposal for a suitable layout for a group of dwellings based on orientation considerations.

DEFINITION OF PERFORMANCE REQUIREMENTS

The design process began with the definition of performance requirements and limit values for the afore-mentioned case of a low-cost house in Temuco. Current regulations for the housing sector provide minimum requirements for the thermal resistance of the envelope, in particular walls, roofs, ventilated floors and partly for glazing. There are no regulations in terms of air tightness, indoor air quality, the thermal resistance of floors, or overall energy demand. In addition, current U value requirements for walls and glazing are considered insufficient in relation to the local climate. In fact, several authors (Escorcia et al., 2012; Celis et al., 2012; Schueftan and Gonzalez, 2013) agree on the shortcomings of the current standard, which does not take into consideration relevant aspects such as thermal bridges, air tightness, the thermal transmittance of glazed surfaces. They also question the values established by the standard due to their deficiency in relation to those in countries with similar climates.

This lack of appropriate performance requirements in current regulations has important implications for the low-cost housing sector. Occupation density is high: dwellings of 42 to 55 m^2 are allocated to families of 4 to 6 people. This results in problems such as poor indoor air quality and high indoor relative humidity, which usually lead to condensation and mould. Apart from these serious building pathologies, fuel poverty generates low thermal comfort conditions, owing to the fact that these families normally cannot afford heating.

An integrated approach to design, construction and post-occupation was adopted for this project; hence, performance indicators and limit values were proposed that went beyond current regulations and were based on international standards and best practices, while keeping in mind the cost constraints associated with low-cost housing (Table 1). Some indicators were also included that are not commonly present in international regulations but are essential in the case of housing in the south of Chile, where condensation and rain penetration through walls pose important risks to dwellings. Recent studies show that these two concerns top the list of

TABLE 1. Performance objectives for the project.

Performance Objective	Limit value OGUC	Limit value IDP
Heating energy demand (kWh/m^2 yr)	n/e	60
Thermal transmittance (U Value) (W/m^2°C)		
Walls	1.6 (Zone 5)	0.6
Roof	0.33 (Zone 5)	0.33
Glazing	n/e	2.8
Air tightness n50 (ach)	n/e	8
Ventilation rate (ach)	n/e	1.5
Condensation risk (HR %)	n/e	90
Rain penetration through walls (Pa)	n/e	600

Limit Value OGUC: Limit values established in the national regulations (Ordenanza General de Urbanismo y Construcción)
Limit Value IDP: Limit values established by the IDP interdisciplinary team
n/e: Non-existent in the current regulations

problems that occupants have in their dwellings, particularly in lower socio-economic groups. Performance indicators were verified using calculation and simulation strategies. Subsequently, they were verified in the construction and post-occupation phases by means of objective measurements with specialized instruments.

INTERDISCIPLINARY TEAMWORK

The design team was composed of architects and engineers; one of the architects led the integrated design process and another was in charge of the housing prototype design. The other members contributed to the team with their respective expertise in energy efficiency, building physics, acoustics, thermal simulations and structures (Figure 1).

The process was characterized by regular design team meetings, followed by meetings with the client, SERVIU, and the contractors, and the Chilean Chamber of Construction, CChC. The development team, made up of the design team, client and contractors, played a key role in the design process. As clients, the role of SERVIU in the design process was crucial because their expert experience in low-cost housing provided relevant information in terms of current regulations, user perception, and socio-cultural factors. In addition, the role of the CChC was also quite important, as they complemented the process with their experience in low-cost housing construction, including cost and technological considerations.

INTEGRATED DESIGN PROCESS

The design process was based on IDP with regard to establishing performance requirements, proposing design strategies, analysing different performance indicators using both simple methods and more sophisticated software, verifying performance requirements and optimising the design of the house in order to achieve those requirements (Figure 2).

FIGURE 1. Interdisciplinary team.

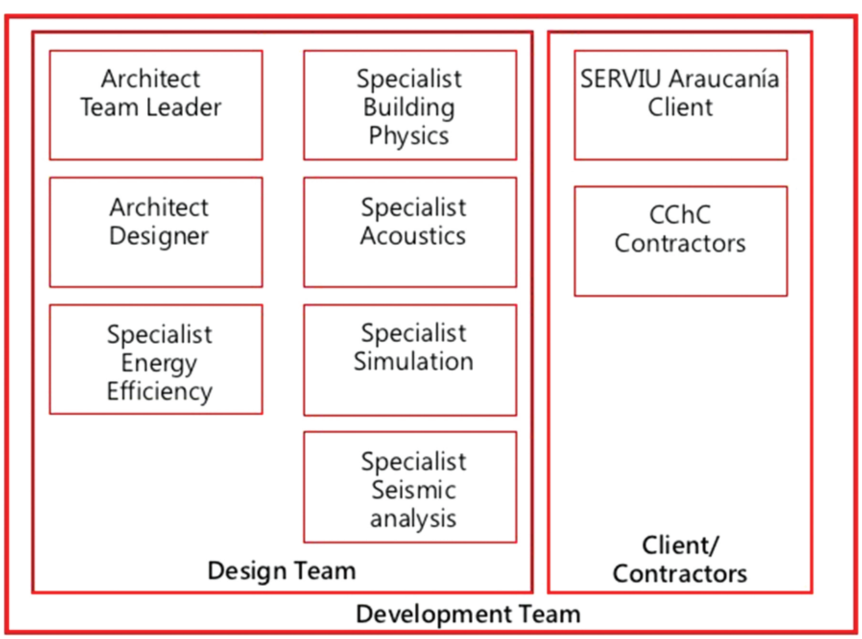
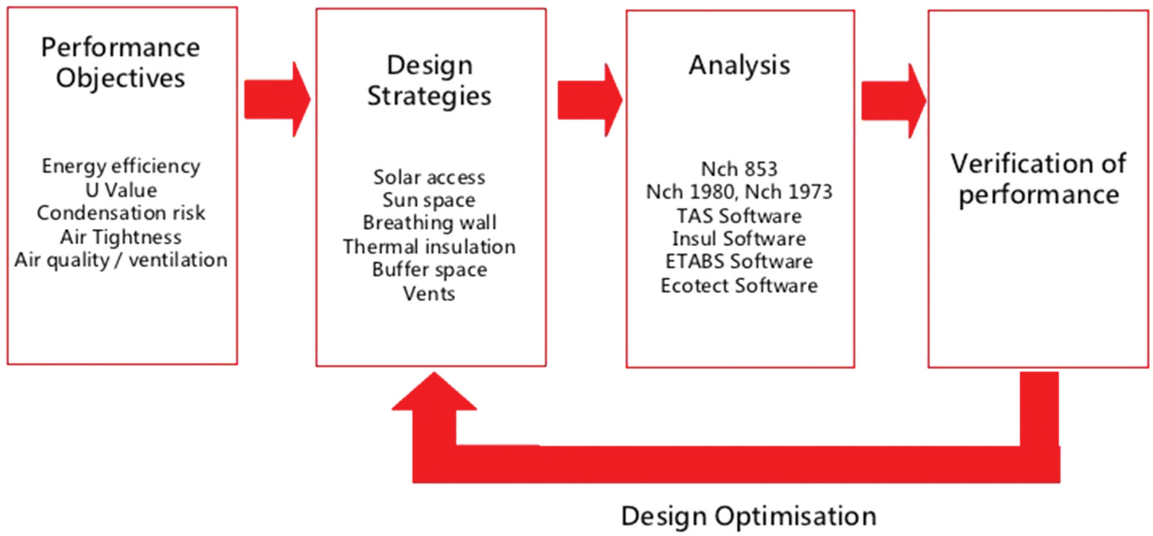


FIGURE 2. Integrated Design Process.



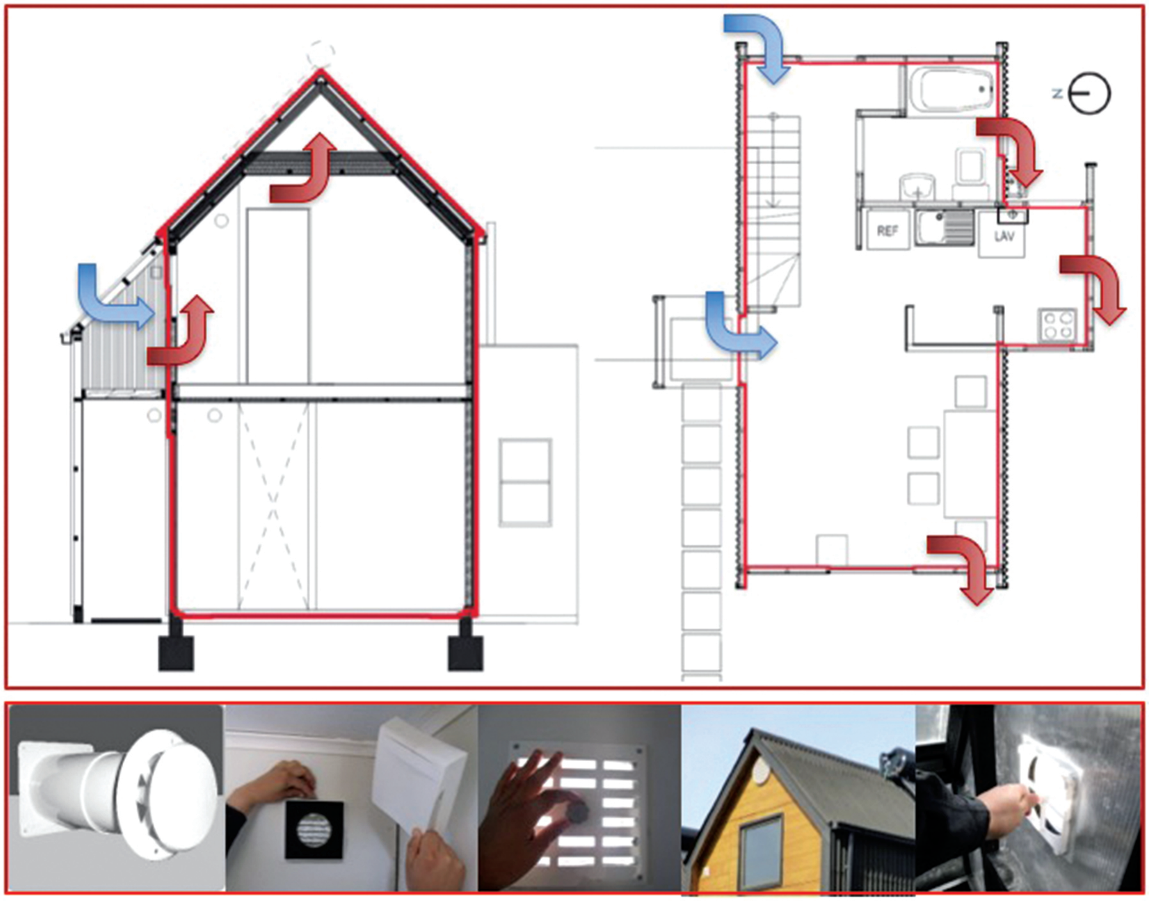
One of the main challenges of the interdisciplinary team was to create strategies to reduce condensation risk in the house. The team devised four different strategies that together achieved this task:

- Locating the damp rooms (bath, kitchen) towards the southern façade so that water vapour generated inside the house could be removed by the negative pressure of the prevailing north wind in winter.
- Incorporating 80 mm of thermal insulation in the walls, based on calculations suggesting that a minimum of 60 mm was sufficient to control condensation risk at 90% internal RH.
- Designing a breathing wall that allows water vapour to travel through its different layers and exit through the ventilated cavity located under the rainscreen.
- Developing a natural ventilation strategy for winter conditions through the provision of vents in outer walls.

The natural ventilation strategy for winter conditions is very important due to the small volume of indoor air and the high occupation density, which result in high air renovation requirements. With 4 occupants in the house, the ventilation rate should be 1.5 air changes per hour. This is achieved through low-cost vents in places that are unlikely to cause uncomfortable draughts for the occupants, such as next to the stairs and in the ceiling connected to the ventilated roof. Diagrams in Figure 3 show the natural ventilation strategy in plan and section, as well as different photographs of the vents located in the sunspace, walls, ceiling and ventilated roof.

The development of the breathing wall represented a major task for the interdisciplinary team, as it had to be structurally resistant to earthquakes and low in cost. Two different solutions for the wall were created, each of which generates the ventilated cavity in different ways, as shown in (Figure 4). The structural resistance of the timber wall is delivered by the outer layer of OSB, so the provision of a simple cavity was difficult to achieve and required testing in the

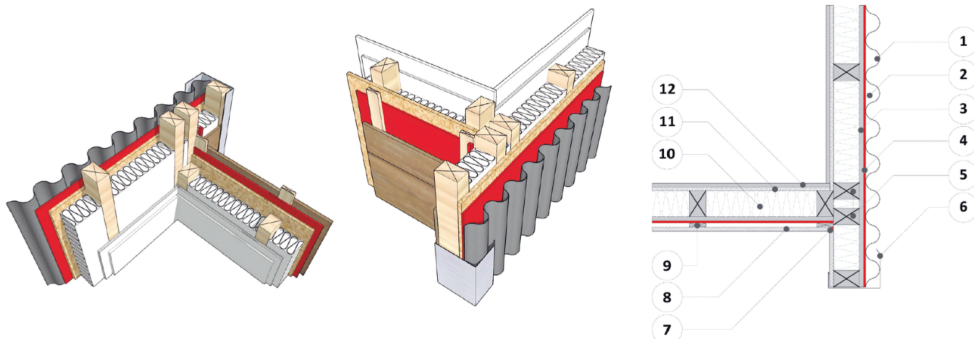
FIGURE 3. Plan and section of the prototype with natural ventilation strategies.



laboratory. The project included a thermal envelope that far exceeds the thermal regulations in force in the General Urbanization and Construction Ordinance or OGUC (MINVU 2006): 80 mm of thermal insulation in walls, 150 mm in roofing, 30 mm under the floor foundation, and hermetically sealed double-glazed windows. In order to reduce the thermal bridges generated by the wood structure, the inner layer consists of a panel composed of a layer of gypsum board and an extra 10 mm layer of expanded polystyrene.

As the client commissioned the design of a prototype, there was thus no specific site for the project during the design stage, and the team developed a layout for a group of the units to explore the best possible orientation. Solar exposure is not normally a design consideration in low-cost housing due to the diversity of sites in a master plan, but in this case the houses were designed to have good solar access from the east, north and west. The width of a typical site for a low-cost house is only 7.2 m. Hence, the separation between the units allowed only the sun from the north to hit the first floor of the house during the whole year, while also hitting the ground floor in summer (Figure 5). Therefore, in this area the team proposed a low-cost sun space that provides the main door with a barrier from the stormy north winds in winter. The habitable spaces of the house, bedrooms and living room, face east, north and west, while the bathroom and the kitchen face south.

FIGURE 4. Detail of the Breathing Wall.



1. Black Onduline fiber-asphalt exterior siding
2. Air chamber
3. Structural OSB, 11mm thick
4. Tyvek moisture and air barrier
5. 2"x3" pine studs
6. Zincalum metal corner trim, 0.5mm thick
7. Polyrethane foam corner seal
8. SmartSide exterior siding, 11mm thick
9. OSB furring, 11mm thick
10. Expanded polystyrene thermal insulation, 70mm thick
11. Expanded polystyrene thermal bridge break, 11mm thick
12. Gypsum board interior cladding, 11mm thick

FIGURE 5. Solar shading study for a group of houses (winter solstice).

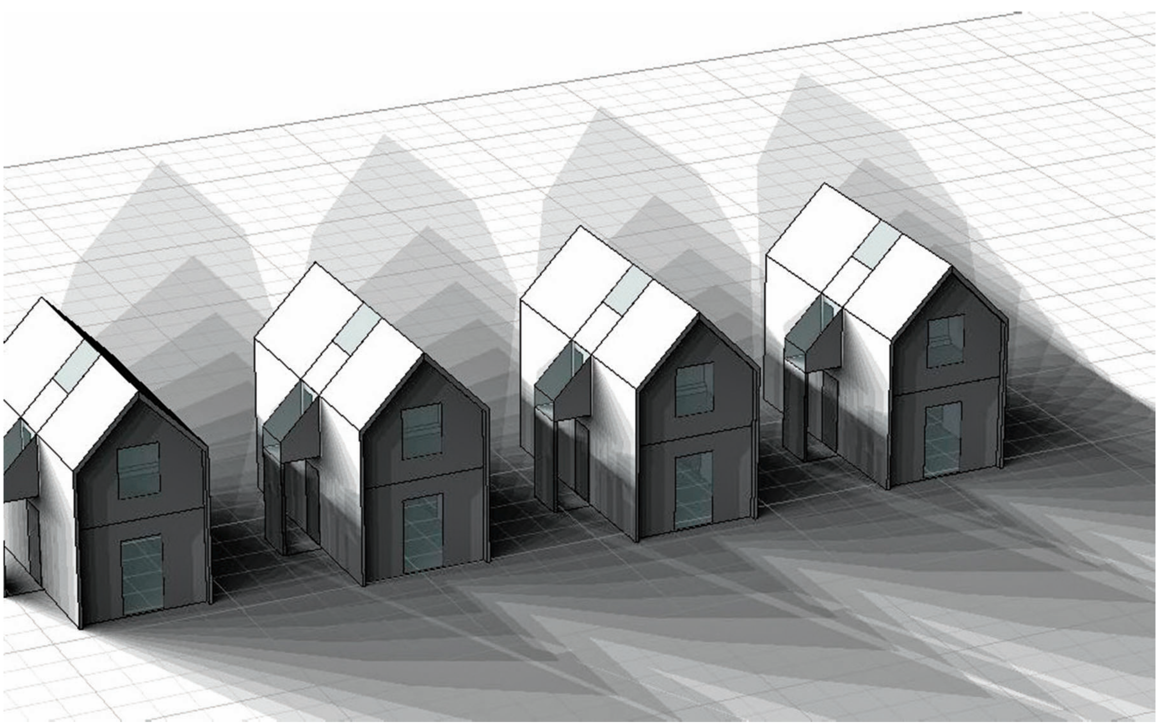
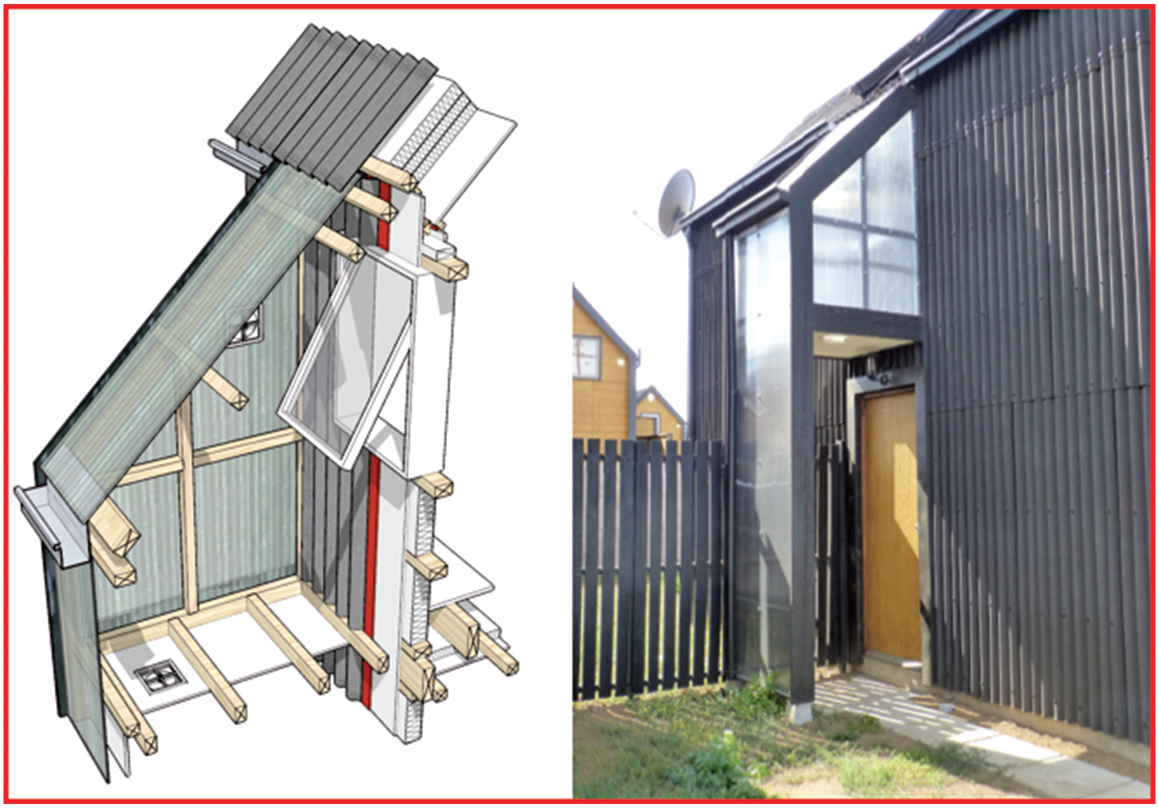


FIGURE 6. Sun space and entry space.



Due to the opportunities for solar incidence, the first floor has a simple low-cost sun space covered in corrugated polycarbonate with a small window that can be opened to connect it to the interior of the house. Thus, on sunny days the space receives abundant solar radiation that generates a greenhouse effect, where the heat generated can enter the house to provide solar gains. In addition, it has vents to the outside and the inside, which allow for the constant flow of preheated air, as well as to control the option of venting only to the exterior in case the hot air generated is not required inside. Furthermore, the wind and rain barrier is a solution that can easily be upgraded by the users to provide an enclosed entry space for the main door (Figure 6).

The final housing prototype has a floor area of 52 m^2 and a selling cost of approximately USD $45,000. Seventeen units were built in a final group layout that favours solar access as was originally proposed. The houses included solar panels for domestic hot water, which are integrated into the roofs (Figure 7).

VERIFICATION OF PERFORMANCE

The construction process, carried out by Rucantú Contractors, was inspected by the team of energy efficiency specialists at CITEC UBB, who checked the thermal insulation installation and the envelope seal. In-situ tests were carried out to verify the performances calculated in the design stage in order to confirm the fulfilment of objectives between the design and construction stages (Figure 8). This process was particularly valued by the SERVIU and local authorities,

FIGURE 7. Photograph of the houses.

since in these cases performance is usually only verified in the design stage. Thermofluxometry, blower door, thermography, air noise isolation and impact noise isolation tests were carried out, among others.

The design process involved several analytical stages that informed many of the design decisions. The design team used a wide variety of methods to verify that the performance requirements established at the beginning of the process were met, from simple calculation procedures

FIGURE 8. Measurements during the construction stage.

TABLE 2. Verification methods in the design and construction stages.

Performance indicator	Verification method in the design stage	Verification method in the construction stage
Heating energy demand	Thermal dynamic simulation software TAS	NO
Thermal Transmittance (U Value) of walls, roof and glazing	Walls and roof: Calculation based on Chilean Norm NCh853 Glazing: specification by provider	Thermofluxometry (U Value) based on ISO 6781 and thermography (thermal bridges)
Air Tightness n50	N/A	Blower Door Test based on ASTM E779-87
Indoor Air Quality and Ventilation	Calculations based on CTE-HS3, UNE 100-012, UNE 100-011	Measurements of CO_2 in post-occupancy stage
Condensation risk	Calculations based on Chilean Norms NCh1980, NCh1971, NCh1973	Test based on Chilean Norm NCh2457
Rain penetration through walls	N/A	In-situ test based on Chilean Norm NCh282

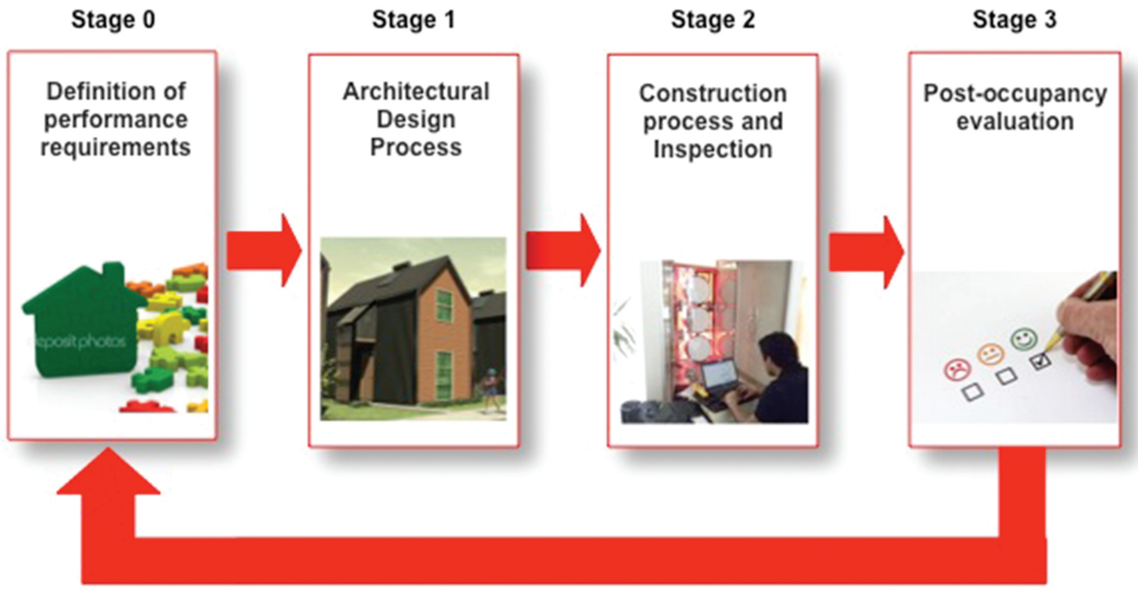
to complex simulation using validated software [Table 2]. The tests carried out showed that almost all of the performance objectives set at the beginning of the process were achieved.

The heating energy demand was calculated by dynamic thermal simulation with TAS software at both the design and post-construction stages, so that the final simulation utilized values for thermal transmittance and air tightness obtained from tests of the real building. These values varied slightly from those calculated at the design stage, as shown in Table 3. The simulation used an indoor design temperature of 20°C during the day (7:00AM to 11:00PM) and 17°C at night (11:00PM to 7:00AM), and internal gains of 160 Wh/m^2 day. The estimated

TABLE 3. Performance data final building.

Performance indicator	Value
Thermal transmittance (U Value) (W/m^2°C) Walls 1 Walls 2 Roof Glazing	 0.62 0.68 0.33 2.57
Air tightness n50 (ach)	8.5
Ventilation rate (ach)	1.5
Heating energy demand (kWh yr)	3184
Heating energy demand (kWh/m^2 yr)	62

FIGURE 9. Closing the loop—stages of the Integrated Design Process.



demand was 62 kWh/m^{2}a, which is only half that of a typical two-storey, low-cost house in Temuco (Bustamante 2009). The calculation of the heating demand estimated heat losses from the natural ventilation system were at a rate of 1.5 ach, which explains why no further reduction was attempted.

CLOSING THE LOOP

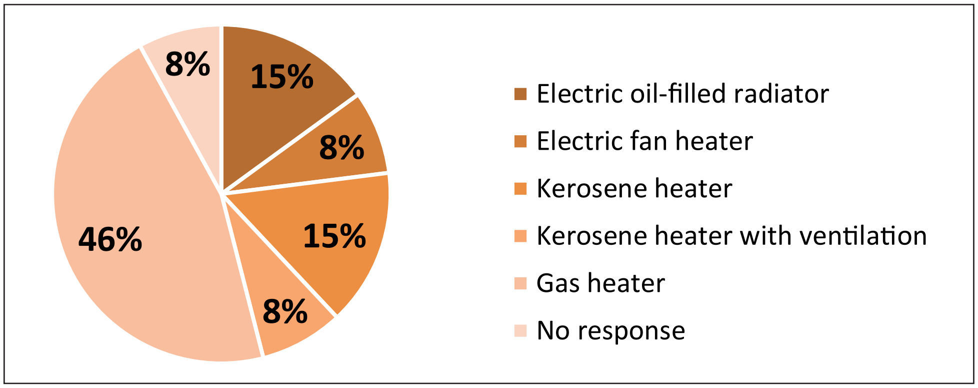
The Post-Occupancy Evaluation (POE) stage is essential for the Integrated Design Process as it makes it possible to close the loop between design, construction and occupancy, in order to inform the design processes of low-cost houses in the future based on the results of this housing prototype. In this case, POE was recorded in a survey that registered the perception of the occupants regarding the features of the house and the achievement of the proposed performance tasks (Figure 9).

In this case, the post-occupancy evaluation was part of a postgraduate thesis (Arce 2016) that analysed thirteen of the seventeen homes built. Frequently, low-cost housing in Chile does not include the provision of a heating system. Therefore, in the design stage of this project, only a space was included for the possible installation of an individual heater hopefully fuelled with pellets. The city of Temuco is characterized by a high degree of air pollution from PM_{10} and $PM_{2.5}$ particulate matter due to the predominant use of wood combustion for heating. For this reason, the new Environmental Decontamination Plan discourages heating systems that use wood as a fuel. The post-occupancy study showed that the majority of dwellings use gas, paraffin and electricity as energy sources for heating (Graph 1).

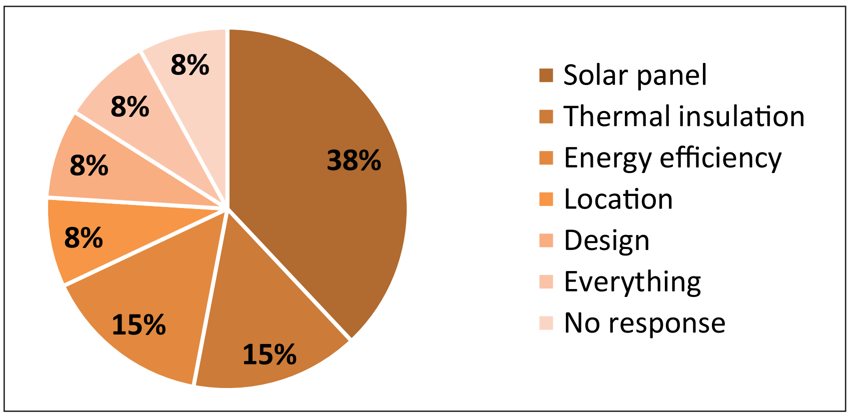
User perception was studied using the BUS methodology developed by Adrian Leaman,[4] which is based on surveys and a comparative benchmarking study with housing in other

4. https://www.busmethodology.org.uk/

GRAPH 1. Survey of heating systems.



GRAPH 2. Occupants' preferred features of their homes.



countries. The users positively evaluated various aspects of the houses, such as air quality and temperature. However, the air temperature in summer tends to vary too greatly and houses overheat at times. Occupants valued appearance, design, comfort and health, while lack of storage space was a frequent criticism. It is important to indicate that the aspects most valued by the occupants of the houses were the solar panels, the thermal envelope and the general energy efficiency (Graph 2).

CONCLUSIONS

This is the first recorded initiative of using the Integrated Design Process to develop a low-cost house in Chile, and the outcome has proved to be highly valuable for all the parties involved in the process. The final result is a group of 17 houses that have much better performance standards than typical dwellings in the area built using traditional practices, but at a similar cost. Local authorities have particularly valued the verification of performance in the construction stage, as well as the documentation of user perceptions in the post-occupation stage. It is expected that these houses will enhance the quality of life of their occupants.

However, the implications of this case are expected to go beyond this specific initiative. The SERVIU is interested in changing the methodology for developing low-cost housing in Chile to promote integrated design and close the loop using post-occupational evaluation, as well as create performance-based regulations for all future low-cost housing regulated by the state. This is a major shift considering current SERVIU regulations are largely prescriptive and the process for developing housing projects is usually linear and centred on the architect.

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