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Article *in* Architectural Science Review · May 2020

DOI: 10.1080/00038628.2020.1764328

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Architectural Science Review

ISSN: 0003-8628 (Print) 1758-9622 (Online) Journal homepage: https://www.tandfonline.com/loi/tasr20

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To cite this article: Gabriel Felmer & Simos Yannas (2020): Designing naturally-conditioned dwellings for warm and cold-temperate regions of Chile, Architectural Science Review, DOI: 10.1080/00038628.2020.1764328

To link to this article: https://doi.org/10.1080/00038628.2020.1764328

ARCHITECTURAL SCIENCE REVIEW
https://doi.org/10.1080/00038628.2020.1764328

Designing naturally-conditioned dwellings for warm and cold-temperate regions of Chile

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ABSTRACT

The central problem addressed by this paper is the fuel poverty experienced in Chile as a result of poor thermal performance of dwellings, a problem commonly encountered throughout the country, even in new housing. The domestic consumption of fuels used for thermal regulation of dwellings accounts for a large proportion of national energy use, gas emissions, and household expenditures. This study aims to alleviate these issues by presenting building designs that can provide comfortable indoor thermal conditions without a need for conventional energy fuels. Following the findings of field studies, the design of standard dwellings has been optimized using computational studies that were conducted with consideration for the country's main climatic regions. The results of this study have shown that the application of passive design measures can be sufficient for achieving thermal comfort conditions, thereby reducing the use of domestic fuels to near-zero levels in most of the country.

ARTICLE HISTORY
Received 15 January 2019
Accepted 29 April 2020

KEYWORDS
Fuel poverty; naturally-conditioned dwellings; near-zero carbon building design; adaptive thermal comfort; occupant controls

Introduction

Fuel poverty, which is defined as an inability to attain adequate warmth and energy services in the home (Liddell 2012; Bouzarovski 2014), is a major global issue. Since the adoption of this term in the 1980s (Lewis 1982), it has been applied by several authors, mostly in European countries (Bouzarovski 2014; Heindl 2015; Healy 2017), to address a wide range of domestic energy issues. In Latin America, fuel poverty has been associated with poor quality housing and low income households that have limited access to domestic fuels (ECLAC 2009; ECLAC 2014; Urquiza et al. 2019). While a large body of research has looked at fuel poverty as a complex socio-economic problem (ECLAC 2014; Urquiza et al. 2019), little has been done to alleviate its effects by improving the thermal efficiency of new dwelling stock (Tirado Herrero 2013; Poortinga et al. 2018; Park, Kim, and Song 2019). However, in the cooler regions of Latin America, where space heating is the main domestic energy use (MINEN 2019), thermally poor housing stock has been identified as a major source of fuel poverty (Schueftan, Sommerhoff, and González 2016), responsible for thermal discomfort (MINEN 2017), seasonal morbidity and mortality (Grass and Cane 2018), toxic indoor gas concentrations (Jorquera et al. 2018), and emissions from inefficient heating appliances (Molina et al. 2017).

In Chile, according to the most recent national household expenditure survey, fuel poverty affects at least 16% of households (Villalobos Barría, Chávez, and Uribe 2019). Residential space heating and cooling accounts for over half the national domestic energy consumption, an annual average of 4,280 kWh per dwelling, of which 96% is used for heating and 4% for cooling (MINEN 2019). Although Chile has a wide range of climates, most of the population is concentrated in its mild climatic regions (INE 2017). Because of this, there is great potential for the application of passive design techniques to greatly reduce the use of conventional fuels throughout the country (Causone et al. 2014; Monge-Barrio and Gutiérrez 2018). The major barriers to implementation include limited knowledge on household fuel consumption patterns (Bunster and Noguchi 2015), expensive energy efficiency measures (Schueftan and González 2015), and a lack of a comprehensive approach to improving thermal comfort (Harkouss, Fardoun, and Biwole 2018).

Housing shortages and the environmental impact of mainstream residential construction with relation to energy use and carbon emissions have placed great pressure on the Chilean government to improve the design of new dwelling stock (MINVU 2017). Present estimations show that the demand for housing has far exceeded the supply of new housing, with more than 400,000 new dwellings beyond what are already being constructed needed every year (MINVU 2018a). Over the last ten years, there has been a sharp increase in the creation of multi-storey apartment buildings, which account for over half of the new dwelling stock (INE 2018). Many of these developments have turned into 'vertical slums', making them unpopular with planners and policy-makers alike (Vergara 2017). Whether this failure was due to the dwelling type is open to question. However, compared to detached housing, apartments provide a more compact and potentially more energy-efficient building form at a significantly lower cost.

Research that has been done on the energy performance of housing has left a number of unresolved issues that need addressing in order to appreciate the extent of fuel poverty (Tirado Herrero 2013; Monge-Barrio and Gutiérrez 2018). For example, studies conducted in Chile have not looked far enough

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into passive design measures for achieving thermal comfort under free-running or mixed-mode operation (Bustamante et al. 2009; Besser and Vogdt 2017). Instead, research has focused on reducing auxiliary energy where acceptable demands of below 5–10 kWh/m^2 year have been achieved in the warmer areas of the country (Bustamante et al. 2009). However, in the cooler regions of central and southern Chile, where fuel poverty is the most severe (Schueftan, Sommerhoff, and González 2016), annual space-heating energy demands could not be reduced below 25–150 kWh/m^2 (Besser and Vogdt 2017).

This paper presents research findings for improved designs of new dwellings in Chile (Felmer 2018). The research aimed to contribute to the issue of fuel poverty by designing buildings that can provide all-year indoor thermal comfort without a need for auxiliary energy sources. The study compared the performances of detached houses and apartments using a range of passive design techniques in the Central (CCh), Northern (NCh), and Southern regions of Chile (SCh). It is expected that the techniques studied here can be used by builders and designers to deliver near-zero carbon dwellings throughout the country. As suggested by recent research on occupant thermal adaptation (De Dear and Brager 2001; Humphreys, Fergus Nicol, and Raja 2007), a broader thermal comfort band was used for the analysis instead of that used in previous studies (Bustamante et al. 2009).

This paper is structured in four sections. The first two sections outline the methodology applied and the techniques considered for improving the thermal performance of dwellings. The third section presents the results of the simulation studies and design research undertaken for the climatic conditions of Santiago (in CCh), Antofagasta (in NCh), and Puerto Montt (in SCh). The fourth section illustrates the proposed designs and discusses their application.

Methodology

The thermal simulations performed for this study were consistent with published research and field studies that have been carried out in occupied dwellings (Schueftan and González 2013; Felmer 2018; Pérez-Fargallo et al. 2018; Rojo, Fissore, and De Herde 2018). The actual household fuel consumption, which was monitored as part of a previous survey (Felmer 2018), was found to be significantly lower than predicted energy use based on national standards (MINVU 2017). Table 1 identifies the sources of discrepancy. As an example, a sample of social housing dwellings investigated in Santiago ($n = 200$) found that consumption was between 5 and 10 kWh/m^2 month, with respective fuel expenditure costs accounting for 10–30% of the monthly income of households (Felmer 2018).

The dwelling models were calibrated against measured data of indoor temperatures and energy use from four case-study dwellings. The field studies used Gemini dataloggers (TGP-4017 Gemini Ltd., U.K.) and a daily questionnaire on occupancy patterns, which showed that auxiliary space heating was used intermittently in individual rooms that were kept at different temperatures (Felmer 2018). As can be seen in Figure A1, a good correspondence was achieved between measured and simulated data, with a mean bias error of between 0.66°C and 0.91°C on all the case studies. The parameters most influencing indoor temperatures were internal heat gains and indoor-outdoor air exchange rates (Felmer 2018).

Scope and criteria of analysis

The thermal simulations were performed for a range of base-case designs and different climatic regions. The national housing stock is composed mostly of detached, semi-detached, and terraced houses (82%) that are primarily of masonry construction (brick and concrete 75%) or timber (25%) (INE 2018). The sample considered in this study included the most and least exposed dwelling types in terms of building form, as well as a mix of lightweight and heavyweight structures. The base-case was drawn from a database of schemes built by the government (MINVU 2020) and adapted to meet typical national characteristics, namely average floor area, glazing area, and number of storeys and bedrooms (INE 2018). It comprised a single-storey detached house and an apartment located on an intermediate floor of a multi-storey building (Figure 1). In accordance with national housing characteristics and statutory thermal regulations (MINVU 2018b), the dwellings had the same plan layout, distribution of glazing areas on the external envelope, and minimum thermal insulation levels for each climatic region. The locations chosen for this study represent the most populated regions of Chile: CCh (61%), NCh (12%), and SCh (23%), comprising over 96% of the existing dwelling stock (INE 2018). According to the Köppen–Geiger classification, these regions feature temperate Mediterranean Csb (Santiago), warm-dry BWh (Antofagasta), and cold-temperate Oceanic Cfb (Puerto Montt) climates.

Occupancy schedules were assumed to follow those of the largest national household group, this being a couple with two children (MDS 2019) where one adult is home for most of the day, the children are at school from 8am to 4pm, and the second adult is at work from 8am to 7pm. The hourly profile of internal heat gains is shown in Figure 2 (MINVU 2017). A constant air infiltration rate of 1.0 ACH was assumed for the base case, which

Table 1. Evidence-based and national standard criteria for energy simulations.

	Evidence-based criteria	National standard criteria[a]
Design temperatures	variable range as a function of outdoor temperature and occupant acceptability	fixed thermostat settings of 20°C (heating season) and 26°C (cooling season)
Conditioned rooms	living areas and bedrooms, unless under-occupied	whole-house heating and cooling energy operation
Number of hours	9–16 h a day, when occupants are at home and awake	24-hours energy operation, allowing 8-hour set-back settings
Supported seasons	3–6-month heating season; 3-month cooling season	6-month heating season; 6-month cooling season
Type of appliance	portable room appliances with no thermostat	centralised heating and cooling appliances with thermostat

[a] Indicative criteria used for estimating space-conditioning energy in dwellings, after MINVU 2017.

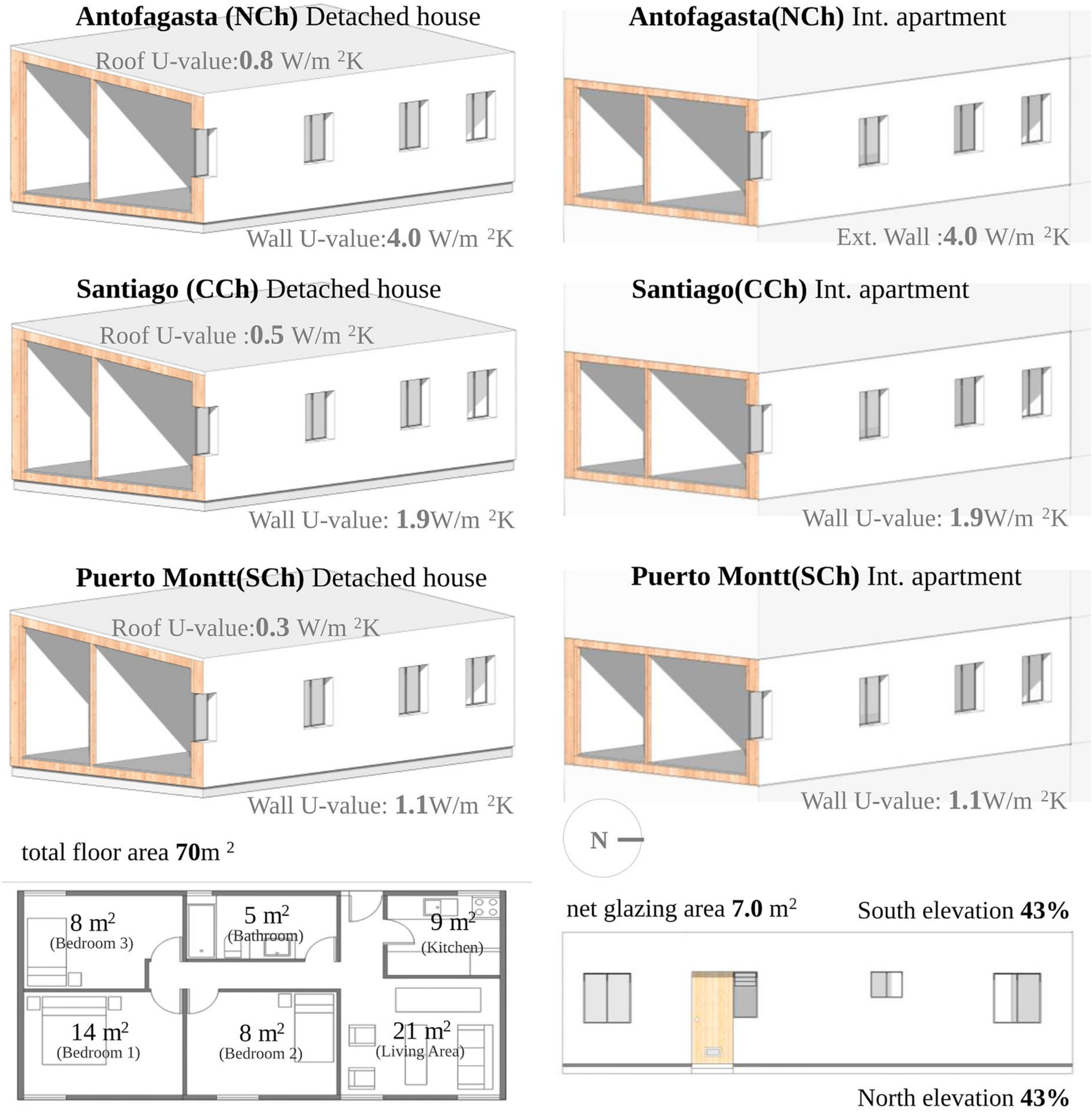

Figure 1. Base-case dwellings used for the study.

is equivalent to some 40 m^3/h per person and compliant with indoor air quality standards (MINVU 2017; Felmer 2018).

For the supported mode, the daily and seasonal space heating and cooling schedules were assumed over 16 h/day (7pm–11pm) with thermostat settings of 17°C from May to September (heating season) and 27°C from December to February (cooling season). Fuel costs were estimated based on the simulated energy demands and compared to the median monthly household income. Carbon dioxide (CO_2) and non-GHG pollutant emissions were also estimated.

For the free-running mode, which is the period of the year during which no auxiliary energy is used for space-heating or cooling, the simulated indoor temperatures were assessed against the thermal comfort band calculated with the expression derived by De Dear and Brager (2001):

$$T_{\mathrm{comf}} = 17.8 + 0.31\,T_o \tag{1}$$

$$T_{\mathrm{lim}} = T_{\mathrm{comf}} \pm 3.5\mathrm{K} \text{ for } 80\% \text{ acceptability}$$

where T_{comf} is the comfort temperature and T_o the outdoor temperature taken as a weighted running-mean (De Dear 2011). The survey that was conducted as part of this research, involving some 200 households in Santiago, showed a close correlation ($r^2 = 0.79$) between the preferred indoor temperature and prevailing outdoor temperature (Felmer 2018), with a comfort band of 7 K width corresponding to 80% of the respondents. This was assumed as an acceptable range for the analysis in this paper.

The effect of different design measures on hourly indoor temperatures and on occupants' thermal comfort was assessed using the TAS dynamic thermal simulation model (EDSL 2016). Weather datafiles were generated with Meteonorm (Meteotest 2016). First runs of the base case detached house and apartment were performed with weather data for Santiago (Meteotest 2016). Hourly results for typical winter and summer days are illustrated in Figure 3. For the base case detached house, on

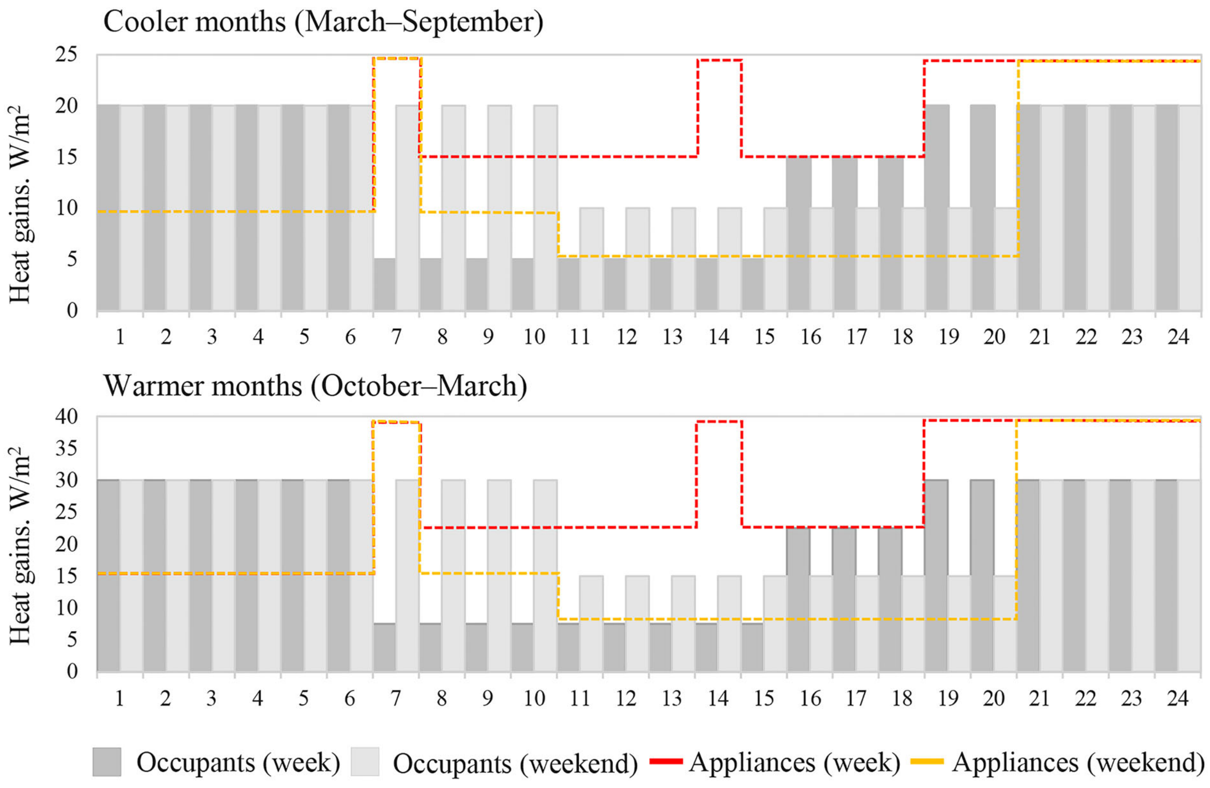

Figure 2. Hourly internal heat loads used for the study.

winter days, room temperatures were shown to fall short of the comfort zone, staying below 15°C for most of the day and falling to very low values at night. Throughout the entire heating season, room temperatures were found to be below comfort for over 68% of the occupied hours. On a typical summer day, room temperatures exceeded the upper limit of the comfort band, with peaks of over 30°C for most of the day. Over the entire summer season, room temperatures exceeded the upper comfort limit for 39% of the occupied hours.

For the base case apartment, lower envelope exposure resulted in higher room temperatures overnight in winter, whereas lower exposure to solar radiation led to lower temperatures during the daytime. Over the entire heating season, room temperatures exceeded the lower comfort limit 62% of all occupied hours. Over the summer period, the apartment experienced a higher percentage of overheating, totalling 48% of all occupied hours.

Further runs were performed for the base case with weather datafiles for Antofagasta (NCh) and Puerto Montt (SCh) (Meteotest 2016). For winter days, Figure 4 shows that the number of daytime hours within the comfort limit decreased consistently from northern to southern locations, ranging from 8 h (NCh) to virtually none (SCh). Over the whole heating season, room temperatures were found to stay below comfort for 12% (NCh) and 80% (SCh) of all occupied hours. On summer days, the base case of NCh presented a level of overheating similar to CCh, with daytime temperatures peaking at around 30°C, whereas for the base case of SCh, underheating was still an issue during much of the day. Over the entire summer, room temperatures exceeded the upper comfort limit on 31% (NCh) and 9% (SCh) of all occupied hours.

Parametric variations

Parametric variations were carried out to assess the potential improvements passive design measures could have on thermal performance. To achieve the target performance criteria for all locations, differences in climatic conditions were compensated for with relevant modifications to the building envelope design. The base case specifications were applied equally to all three locations and led to annual space-heating energy loads of 12–50 kWh/m^2 floor area. These were for a lightweight, timber-frame construction with statutory U-values for walls and roof, 10% Glazing-to-Floor Ratio (GFR), and single glazing on windows. A summary of regional parametric variations is presented in Table 2. The building envelope specifications used for these simulations are illustrated in Figure 5 as step-by-step individual and cumulative variations. These were applied to:

- Ensure the availability of sufficient ***thermal mass (step 1)*** in the building structure and interior surfaces of habitable rooms.
- Provide additional ***thermal insulation (step 2)*** for external walls and, where required, ground floor elements.
- Adjust ***window size (step 3)*** as a function of orientation, room size, and desirability of passive solar heat gains (glazing size increased and redistributed between North and South orientations).
- Provide internal ***insulated shutters (step 4)*** on exposed glazing for control of excess heat loss during evenings and overnight.
- Provide ***controllable ventilation (step 5)*** through trickle vents, auxiliary fans, and/or heat-recovery ventilators.

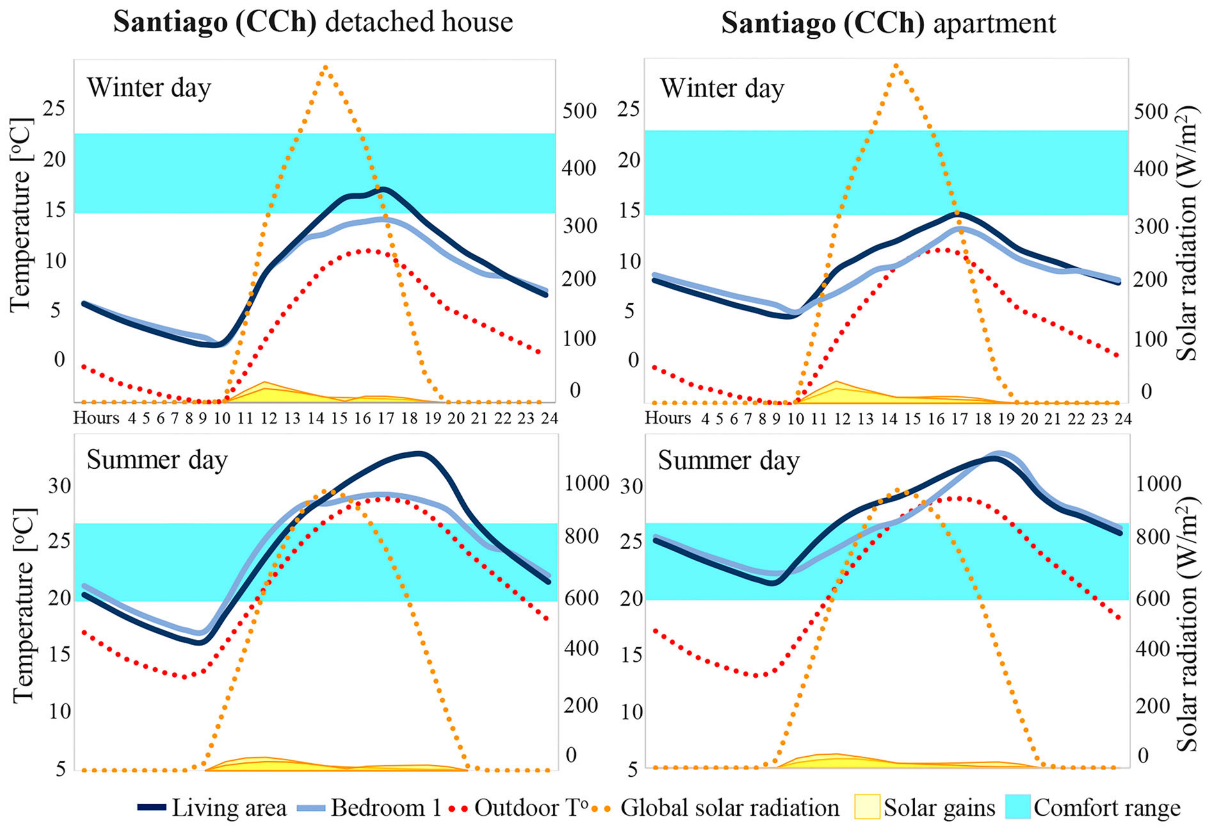

Figure 3. Performance of the base case house and apartment.

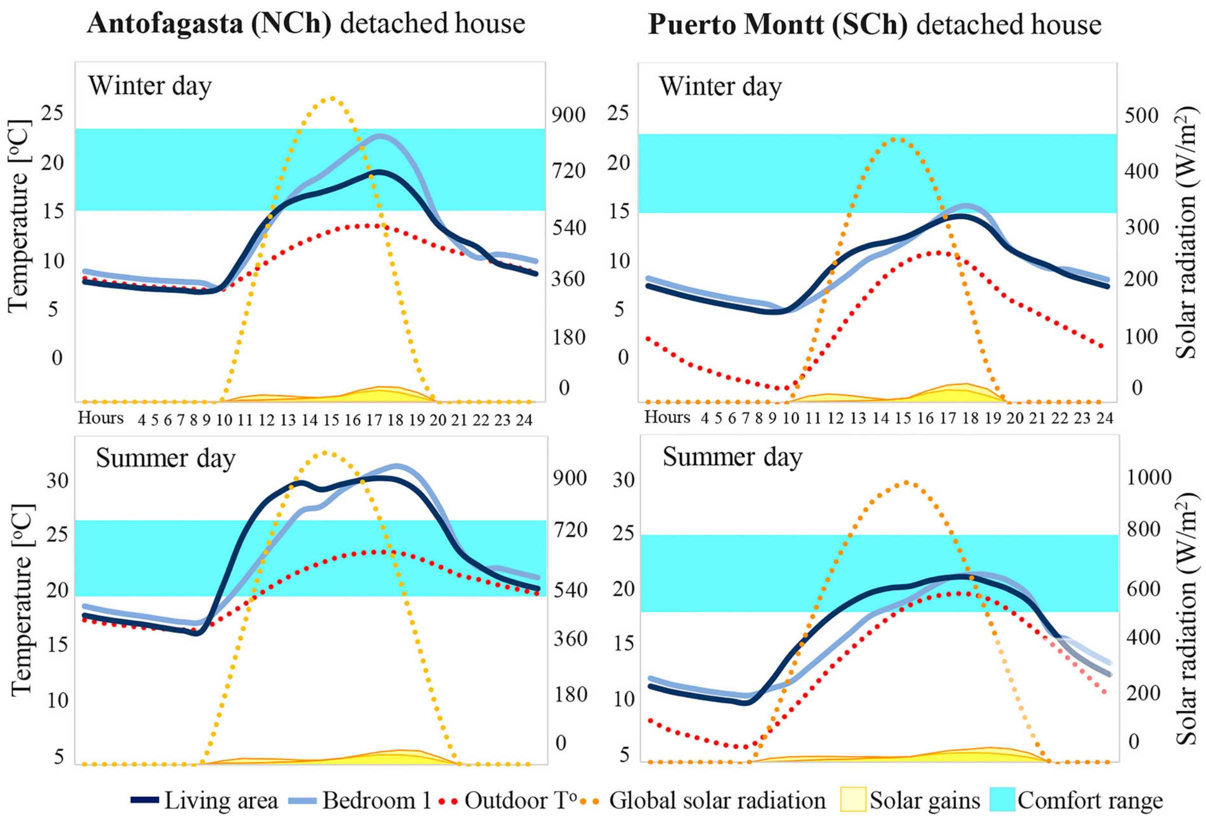

Figure 4. Regional performance variation for the base case detached house.

Table 2. Parametric design specifications.

Location	Dwelling type	Step 1 level of thermal mass	Step 2 exposed wall U-value	Step 3 room glazing size	Step 4 internal insulated blinds	Step 5 min. room ventilation (winter)	Step 6 exterior shading louvers	Step 7 window openings (summer)
			W/m^{2}K	GFR	W/m^{2}K	ACH	SF	ACH[a]
(NCh) Antofagasta	Detached house	MW*	2.0	20%	-	1.0	0.3	20
	Int. apartment	MW*	4.0	18%	-	1.0	0.3	30
(NCh) Santiago	Detached house	HW*	0.5	18%	1.1	0.5	0.4	10
	Int. apartment	HW*	1.0	16%	1.1	0.5	0.4	20
(NCh) Pto. Montt	Detached house	MW*	0.3	16%	0.8	0.2	-	5.0
	Int. apartment	MW*	0.6	14%	0.8	0.2	-	5.0

[a] Average room ventilation rate at the time windows are opened according to specified patterns (Felmer 2018).

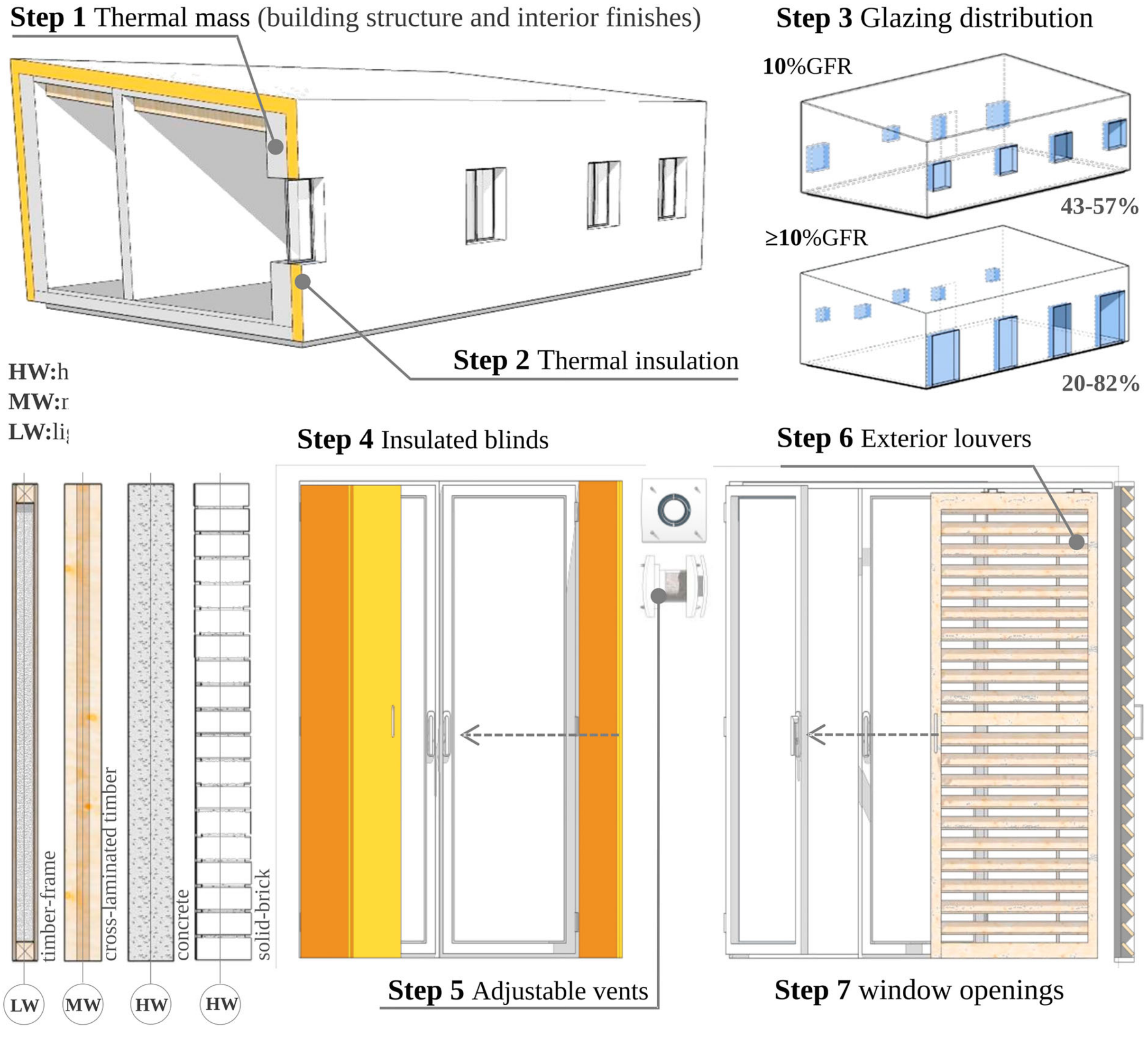

Figure 5. Range of building envelope designs.

- Provide ***adjustable louvers (step 6)*** on north, east, and west facing windows for control of excess solar heat gains.
- Make provisions for heat dissipation and night-time cooling by adequate placement and specification of ***openings (step 7)***.

The results of the simulations are summarized below.

Thermal mass (step 1)

The use of heavyweight masonry construction in place of timber-frame was found to have significant effects in aiding moderate to large diurnal temperature swings in CCh. As can be seen in the base case detached house in Santiago (Figure 6), the improved brick masonry construction reduced peak-to-peak room temperatures by as much as 5–7 K throughout the year. These resulted

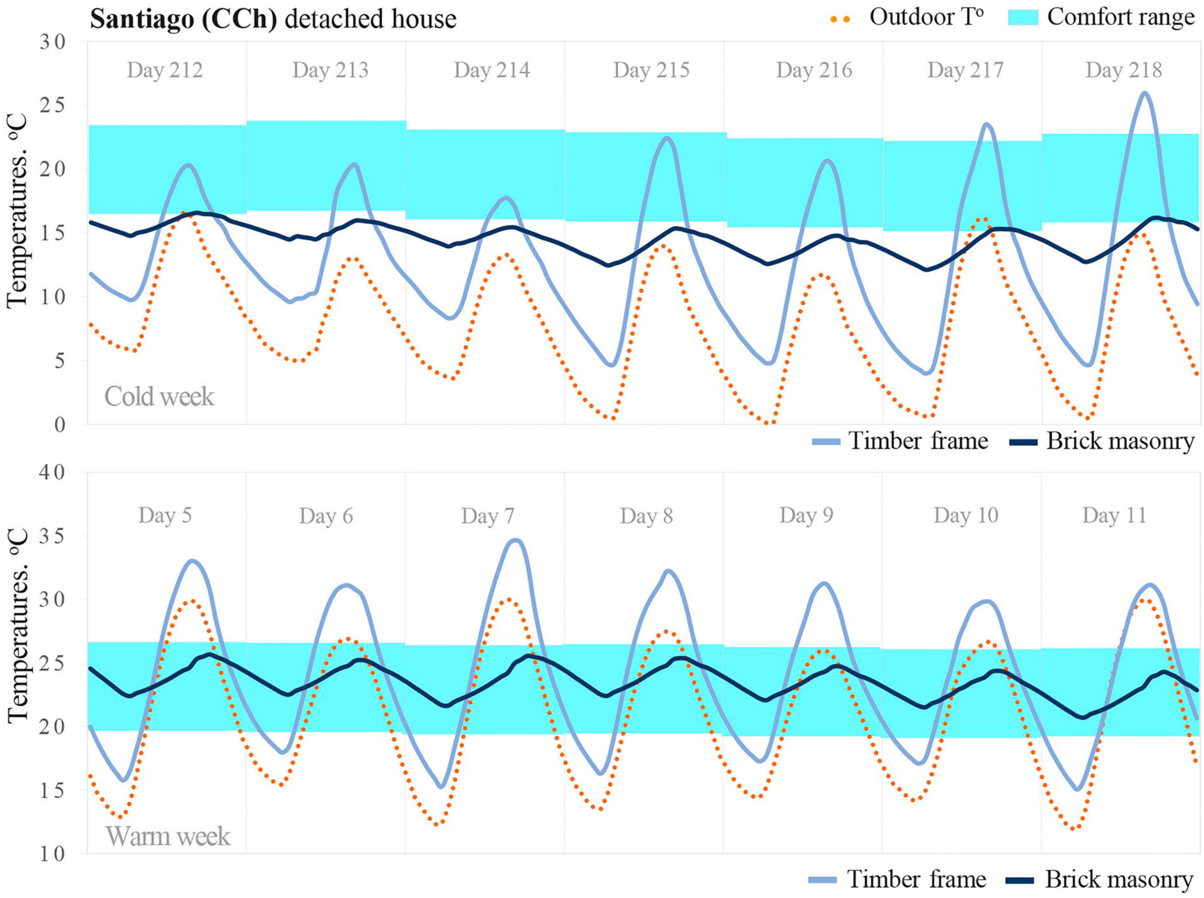

Figure 6. Effect of increasing thermal mass.

in minimum temperatures of around 13°C in winter and high temperatures of 25°C in the summer (Figure 6). In the North and South coastal locations, the heavyweight construction was less effective, reducing peak-to-peak temperatures by around 2.5 K throughout the year (Felmer 2018).

Thermal insulation (step 2)

The addition of external wall insulation contributed significantly to improving thermal comfort in all three regions, raising winter temperatures by some 2 K with no penalties to comfort in summer. In CCh, as shown in Figure 7(a), the addition of wall insulation (U-value reduced from 1.9 W/m^{2}K to 0.5 W/m^{2}K) raised winter room temperatures to comfort levels with daily mean values reaching 17°C, with no additional insulation required on other building elements. In SCh, as shown in Figure 7(b), this measure actually had a beneficial effect in the summer as well.

Glazing size (step 3)

Larger glazing-to-floor ratios than the minimum standard were found to provide additional solar heat gains to achieve comfort temperatures during the daytime in winter in CCh and NCh. As shown for CCh in Figure 8(a), increasing the room GFR from 10% to 18% raised winter temperatures to daily mean values of around 20°C, without exceeding summer comfort limits. This measure was found to achieve both summer and winter comfort in SCh as well (Figure 8(b)).

For the apartments, minor additional measures were needed to meet similar room temperatures. Compared to the detached houses, the daily temperature pattern in the apartments tended to be more stable, as well as more responsive to variations in the building specifications. In CCh, significantly less additional insulation material (−75%) and fewer glazing surfaces (−13%) provided daily temperatures of around 20°C. Although these measures raised room temperatures above comfort over the warmest weeks, the compensatory cooling effects of using shading louvers and window openings were much greater and evenly distributed over time (Figures A2 and A3).

Insulated shutters (step 4)

Use of insulated blinds during the evenings and nights helped reach winter comfort temperatures in CCh and SCh. With regards to the detached house in CCh (Figure A4(a)), increases in mean daily room temperatures of 1.5 K were seen, rising to above 2 K at night. A larger effect was seen in the apartment of SCh (Figure A4(b)), where increases in room temperatures exceed 4 K during the evenings.

Controllable ventilation (step 5)

In the case of the detached house of SCh (Figure 9(a)), by reducing room ventilation rates from 1.0 to 0.2 ACH, the mean daytime room temperatures were raised by 3 K in the winter. The same measure, when applied to the apartment of SCh, had an even

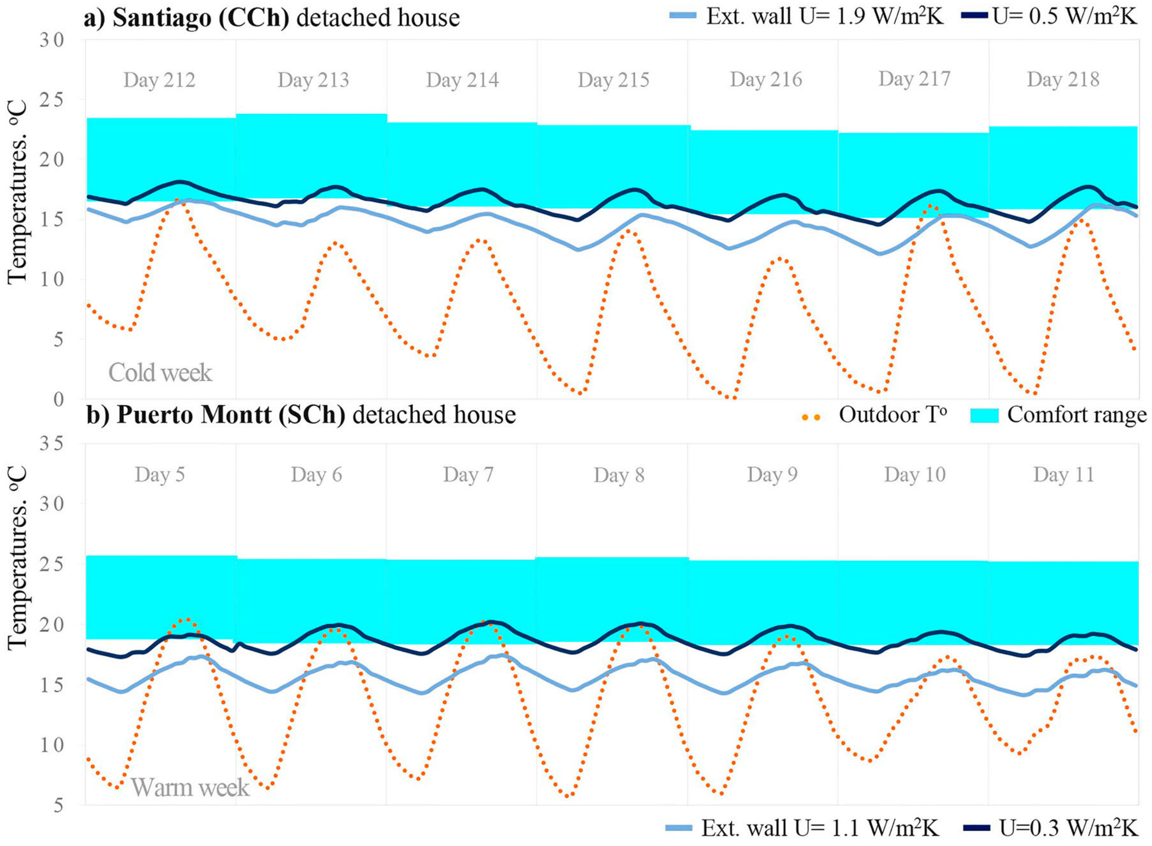

Figure 7. Effect of increasing wall thermal insulation.

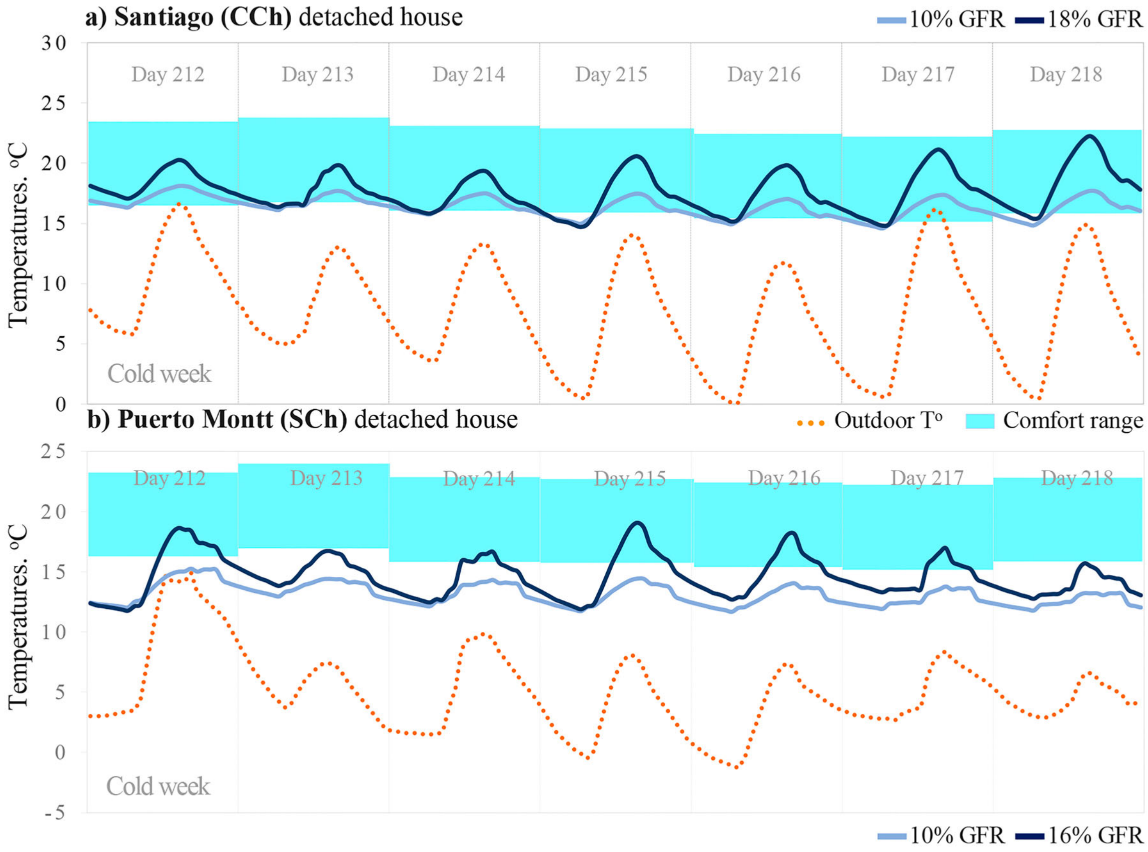

Figure 8. Effect of increasing room glazing size.

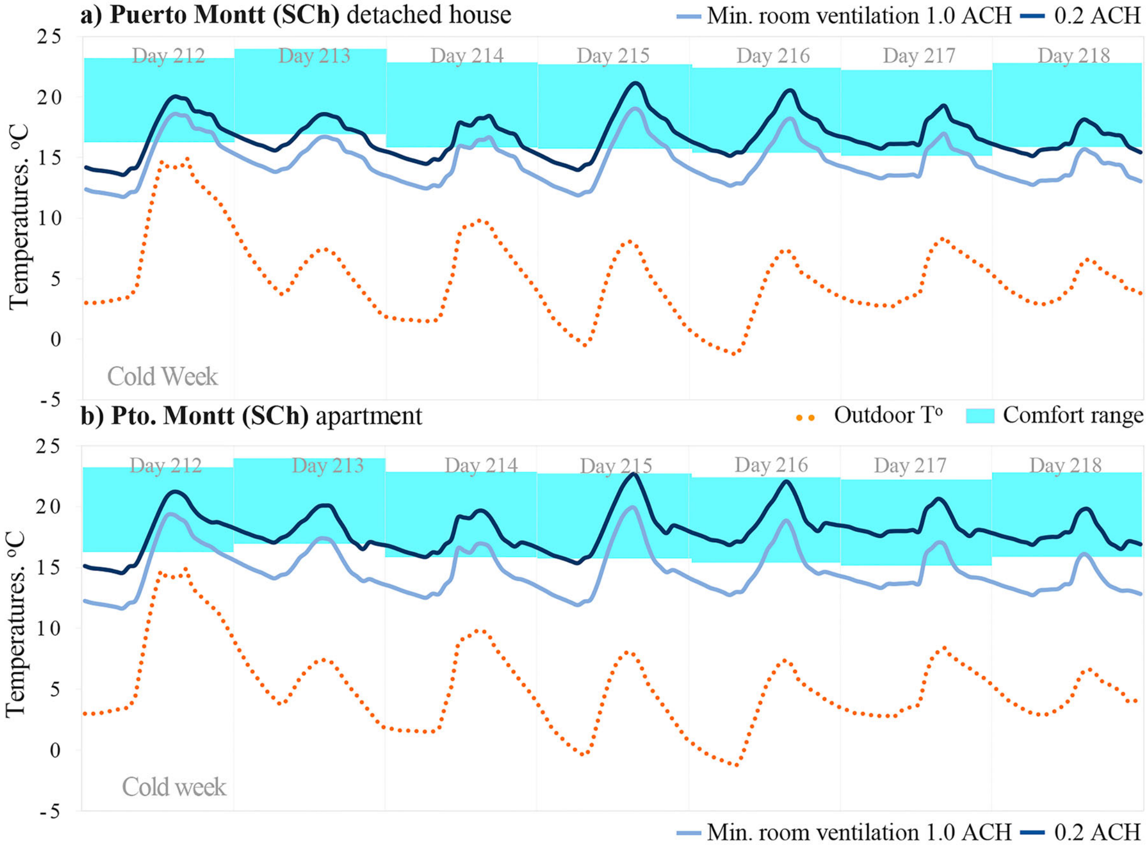

Figure 9. Effect of opening trickle vents.

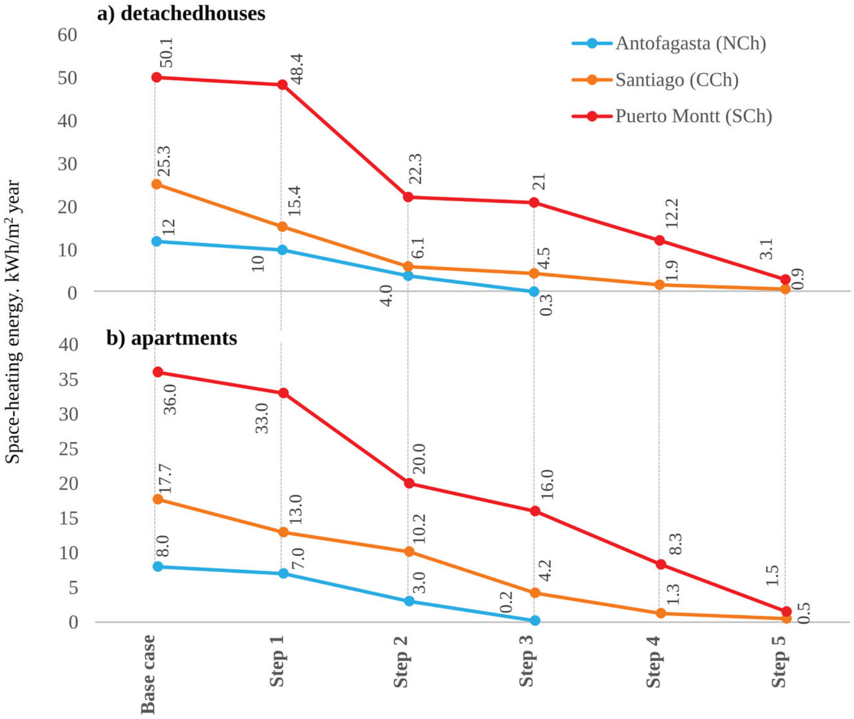

Figure 10. Regional variations in space-heating energy.

stronger effect (Figure 9(b)). Besides improving winter comfort in CCh and SCh, the use of passive vents was also found to be effective for allowing temperature adjustments of ± 2 K over the mid-season weeks (Felmer 2018).

Adjustable louvers (step 6)

In the warm seasons of CCh and NCh, it was found that occupant thermal discomfort could be avoided by minimizing heat gains

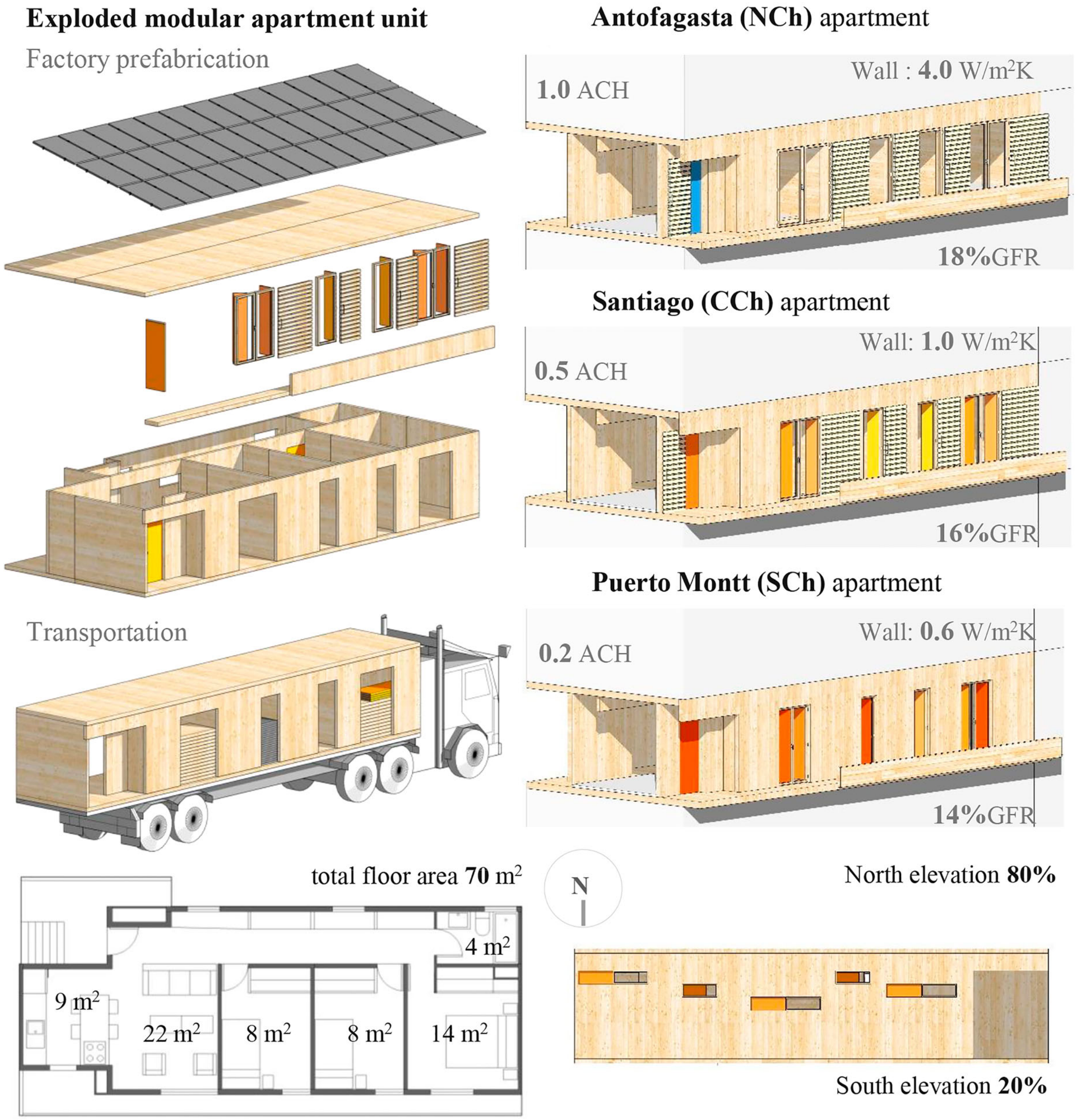

Figure 11. Timber apartment module and regional design specifications.

through glazing. As shown in Figure A2(a) the effect of using exterior louvers was significant in lowering room temperatures by 2 K during peak daytime hours for the detached house of CCh, which has similar summer conditions to NCh. Applying the same measure to the apartment contributed a larger reduction of over 4 K (Figure A2(b)).

Window openings (step 7)

A sensible operation of windows was identified as a primary means of occupant-adaptive behaviour for day-to-day changes in outdoor conditions. For CCh, opening windows in the evenings and at night-time was found to be very effective in helping to maintain summer comfort temperatures. As shown in Figure A3(a and b), a window opening equivalent to some 5% of a room's floor area (from 8pm to 8am) was able to cool rooms by 3 K in the detached house and by as much as 6 K in the apartment. For all locations and dwelling types, the opening and closing of windows allowed adjustments in room temperatures of ± 3 K over most of the year (Felmer 2018).

By applying these measures, the space heating energy demands were reduced by over 94% for all three regions. As shown in Figure 10(a), the most influential measure in reducing the energy demands of the detached house was adding wall insulation (step 1), which led to annual savings of up to 26 kWh/m^2 (52% reduction) in SCh. An important measure in CCh was using heavyweight construction (step 2), which saved about 5–10 kWh/m^2 per year (37–39%). For the apartments of CCh and SCh, the combined effect of optimizing glazing and applying blinds (steps 3–4) contributed as much as 10–30 kWh/m^2 year, which amounted to 50% for CCh and 68% for SCh. The results also confirm that, at any given point, the

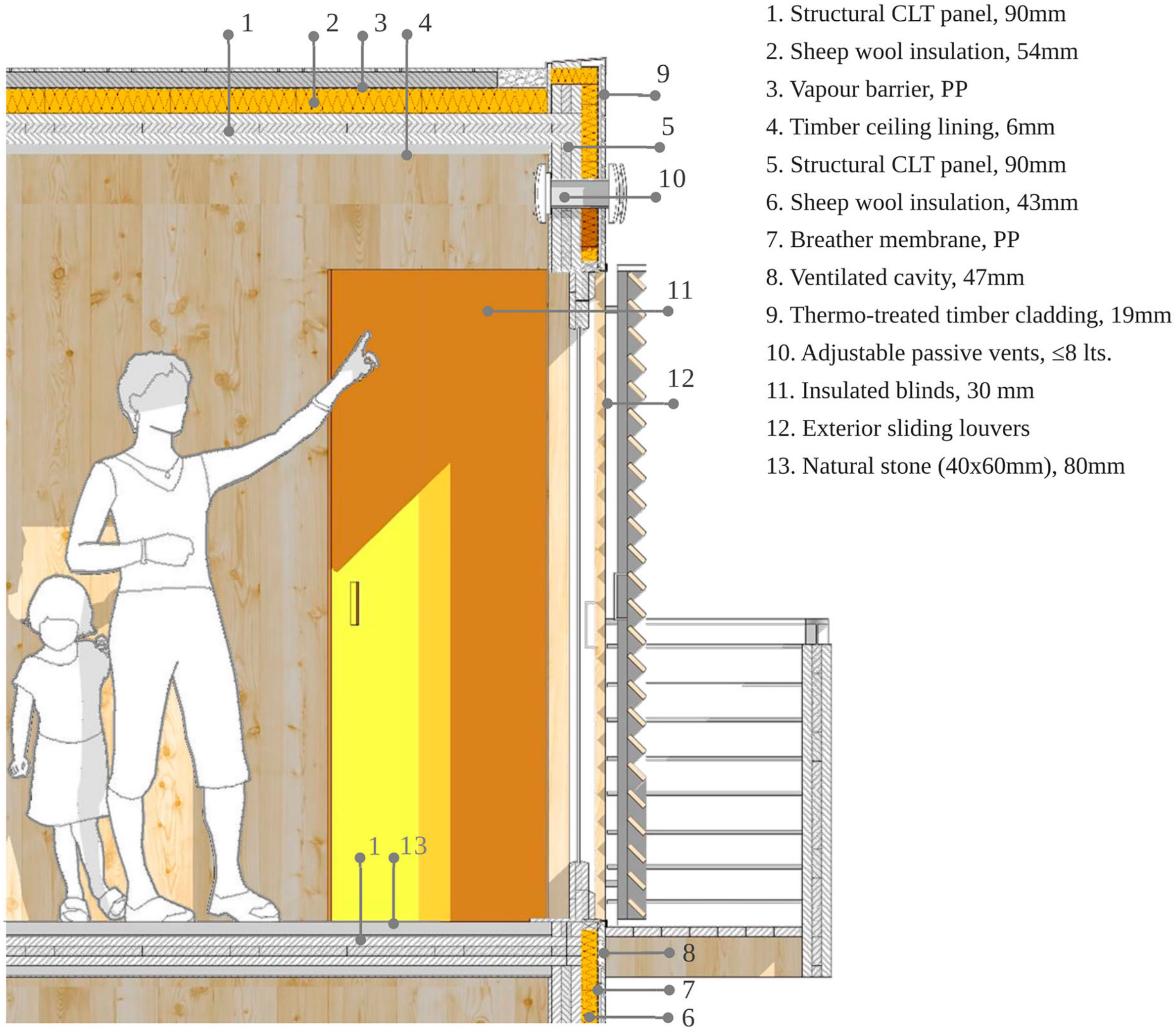

Figure 12. Indicative construction details for timber passive envelope design.

apartments can be more energy efficient than the detached houses.

Design proposals

Based on its findings, this study is proposing a strategy for delivering near-zero carbon dwellings. Among the options considered, timber construction was found to have many advantages for the entire nation (Schmitt 2012; Felmer 2018); Chile has one of the ten largest forestry industries worldwide (FAO 2018), and timber construction is supported by central government in promoting local industry, reducing energy import dependency, and decarbonizing the construction sector (Salas et al. 2016).

The proposal, illustrated in Figures 1112–13, consists of a timber-framed dwelling module that is easy to transport and assemble and can be used to build a range of multi-unit apartment configurations. Figure 11 shows regional design variants for an apartment unit on an intermediate floor, based on the results of simulations for CCh, NCh, and SCh. The timber envelope system, shown in Figure 12, was designed for locally sourced natural materials and finishes to be integrated into prefabricated cross-laminated timber (CLT) panels. The design of the modular unit is currently being finalized for a pilot application that is to be built later this year (2019) in Santiago as part of the first national zero-carbon development (Figure 13).

The modular CLT construction system has great potential for reducing the carbon emissions of new housing (Jara 2015). As an indication, it was estimated that to build a single apartment module requires some 62 m^3 in structural CLT panels, and approximately 856 $kgCO_2/m^2$ would be captured from the atmosphere during the growing of the trees (Felmer 2018). During manufacturing and construction, the CLT unit would emit 128 $kgCO_2/m^2$ less, respectively 34% and 44% less, than the traditional brick masonry and concrete alternatives. Furthermore, the CLT envelope would reduce annual emissions by some 10–60 $kgCO_2/m^2$ due to savings in operational energy.

The simulation results demonstrated that it is possible to do away with conventional space heating and cooling equipment. From the coolest location (Puerto Montt) to the warmest (Antofagasta), the resultant indoor temperatures of the improved dwelling designs were found to be within comfortable levels virtually all-year round. As can be seen in Figure 10, the space-heating energy demands of the detached houses and apartments fall below 3.1 kWh/m^2 year, which is near zero over

Figure 13. Massive-timber apartment development for inner-city Santiago.

Table 3. Savings in space-heating energy and extra capital costs.

	Detached houses 17°C thermostat (16 h)			Detached houses 20°C thermostat (24 h)		
	NCh Antofagasta	CCh Santiago	SCh Pto. Montt	NCh Antofagasta	CCh Santiago	SCh Pto. Montt
Base-case dwellingkWh/m^2 year	**12**	**25**	**50**	**30**	**100**	**130**
Extra-capital costUSD/m^2	24	36	40	24	36	40
Improved dwellingkWh/m^2 year	**0.3**	**0.9**	**3.1**	**2.8**	**5.1**	**11.6**
Extra-capital cost per saved energy	2.1	1.4	0.9	0.9	0.4	0.3
Cost-benefit ratio[a] 10 years	**1.4**	**2.0**	**3.7**	**3.3**	**6.3**	**7.9**
Cost-benefit ratio[a] 30 years	11.5	16.8	27.6	25.3	52.6	66.1
Discounted paybackperiod[a]	**8.0**	**5.9**	**4.0**	**4.3**	**2.2**	**1.8**

[a] See detailed calculation procedures in (Felmer 2018, 22–23).

a geographical region that comprises some 96% of the country's existing dwelling stock (INE 2018).

The study also helped identify a number of relevant additional benefits:

> *High profitability* for private owners and developers. The extra capital costs of the proposed measures are estimated at 24–40 USD/m^2 (Table 3), which is 5.6–9.3% of the minimum budget allocated to social housing (MINVU 2019). With regards to the apartments, the extra capital investment is estimated at 10–30 USD/m^2. Including fuel savings, payback periods are estimated to range from a maximum of 8 years in Antofagasta to as low as 4 years in Puerto Montt. Public developers can achieve payback periods below 5 years for apartments and/or housing requiring high energy usage (e.g. households using continuous central heating at 20°C [Table 3]).
>
> *Large monthly savings* in space-heating energy for future households. Depending on fuel prices, heating schedules, and thermostat settings, monthly savings in space heating costs could be over 180 USD, which is more than 60% of the monthly income of a median low-income household. As shown in Figure 14, for CCh and SCh, respective monthly savings in space heating costs represent 28–37% of the poorest income quintiles (MDS 2019). For higher income groups, which utilize provisions such as central heating, even larger savings could be achieved, of over 260 USD (Table 3).
>
> *Improved environmental quality:* As well as achieving all-year indoor thermal comfort, the improved designs with larger

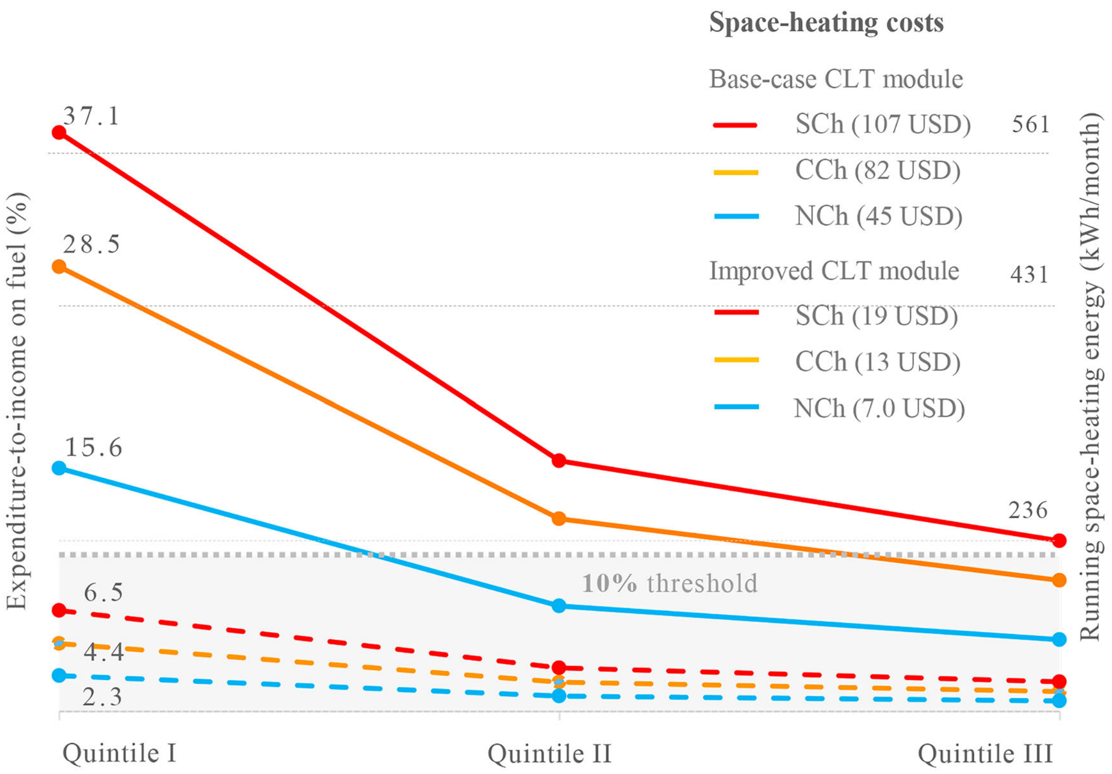

Figure 14. Expenditure-to-income on electricity for space heating.

glazing areas contribute to daylighting, increasing average daylight factors by some 15% (NCh) and 10% (SCh), and providing better control thereof by use of operable shading devices in summer. Ensuring adequate rates of fresh air supply through operable means contributes to maintaining indoor air quality. Reduced emissions of $PM_{2.5}$, CO, NO_2, and SO_2 are estimated to be within 18–128 mg/m^2 per dwelling, increasing from the warmer locations to the cooler regions.

Conclusion

The research discussed in this paper has provided a better understanding of the role of dwelling thermal efficiency in helping to alleviate fuel poverty in Chile. The study encompassed the main climatic regions and common dwelling types and construction systems. From the range of designs that were considered, the use of CLT was found to offer the greatest potential for achieving near-zero carbon housing in Chile. The analysis throughout the paper proved that achieving near-zero energy for space-conditioning is an economically viable option for most of the country. Considerably more work will need to be done to address residual energy use in housing (e.g. water-heating, electricity, and/or cooking) and reduce carbon emissions in construction through innovative design and scale-up of locally manufactured massive-timber envelope constructions.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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Appendix

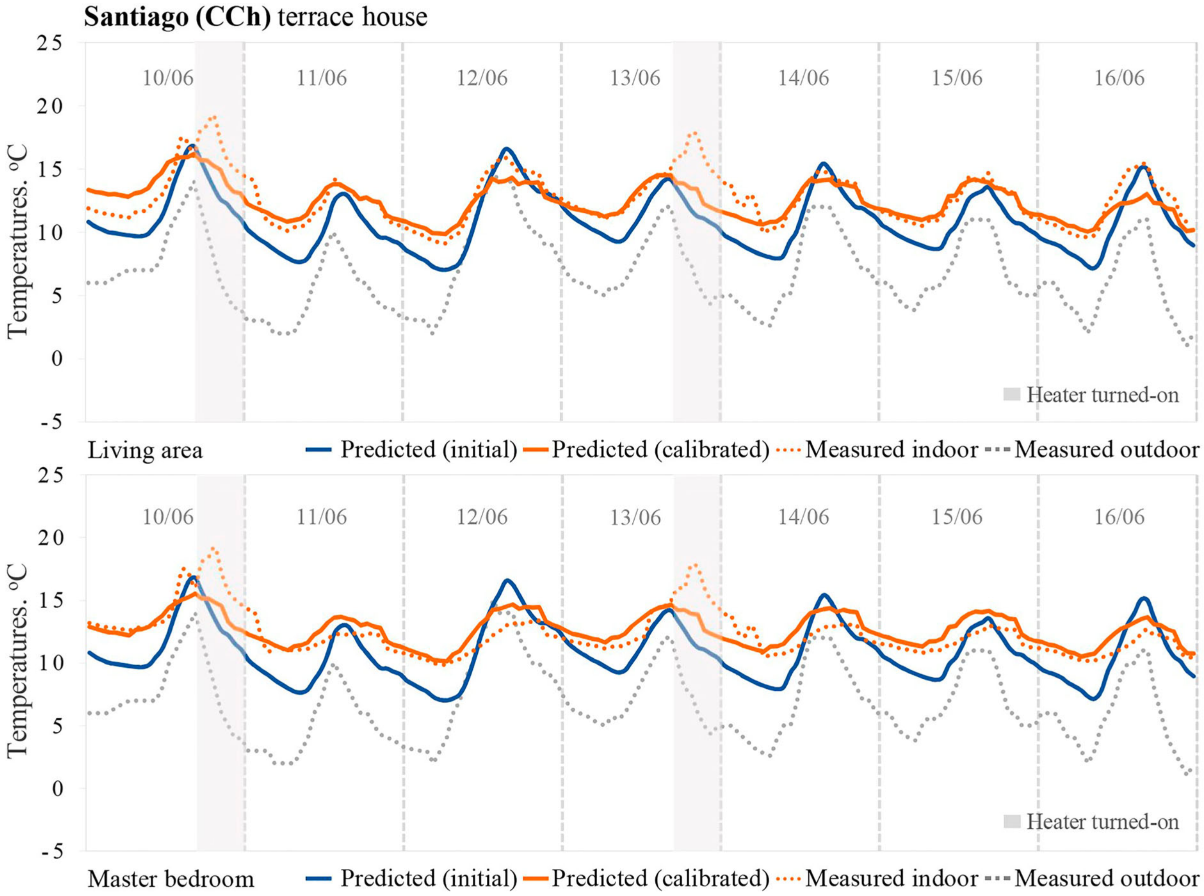

Figure A1. Calibration runs against measured temperature data.

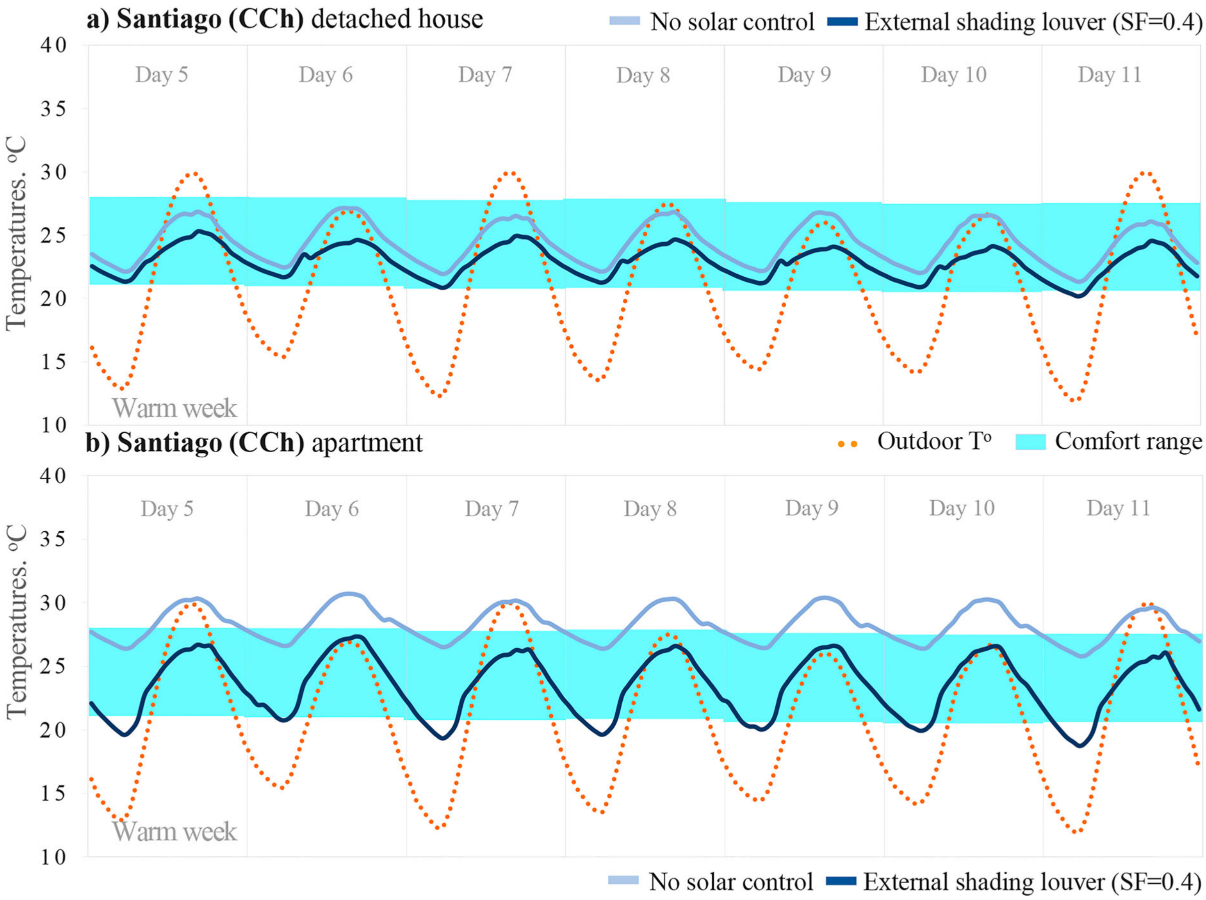

Figure A2. Effect of using exterior louvers.

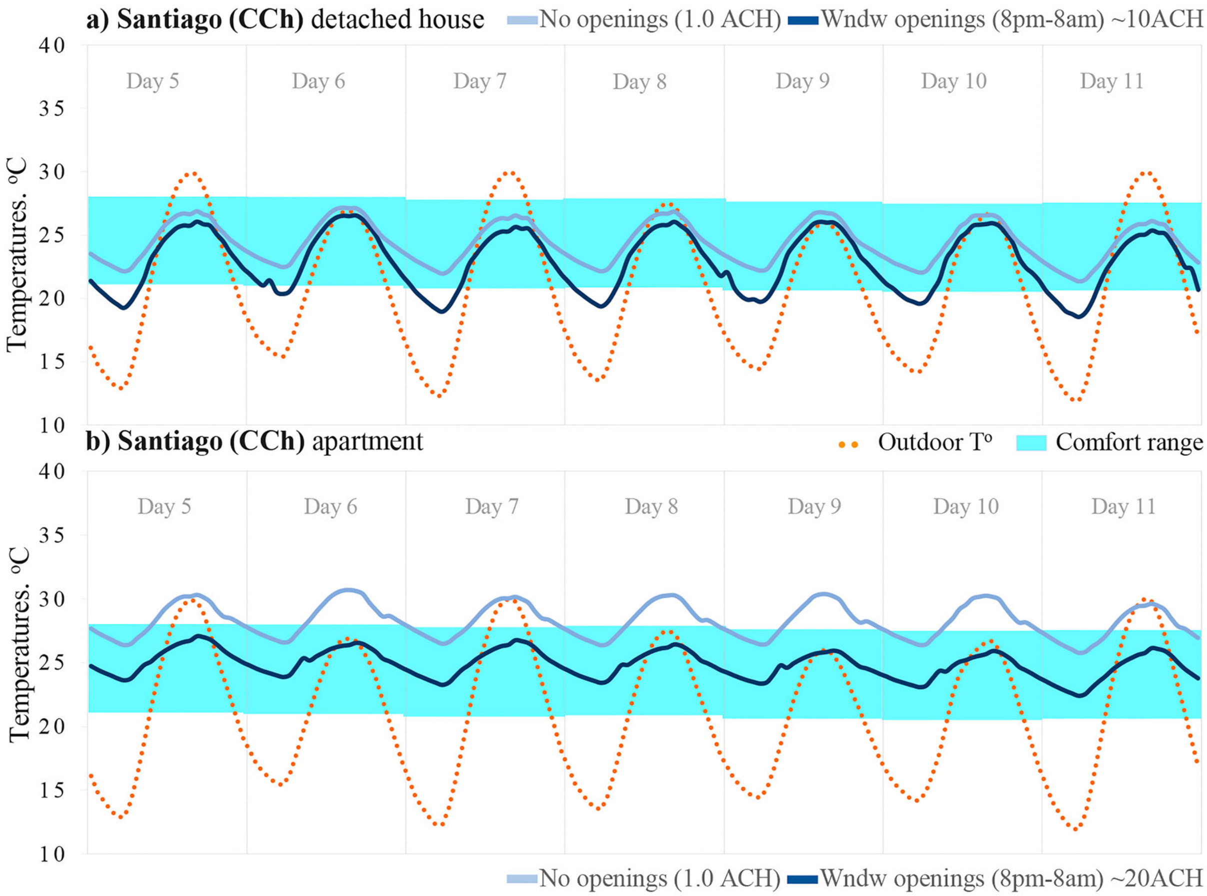

Figure A3. Effect of opening windows.

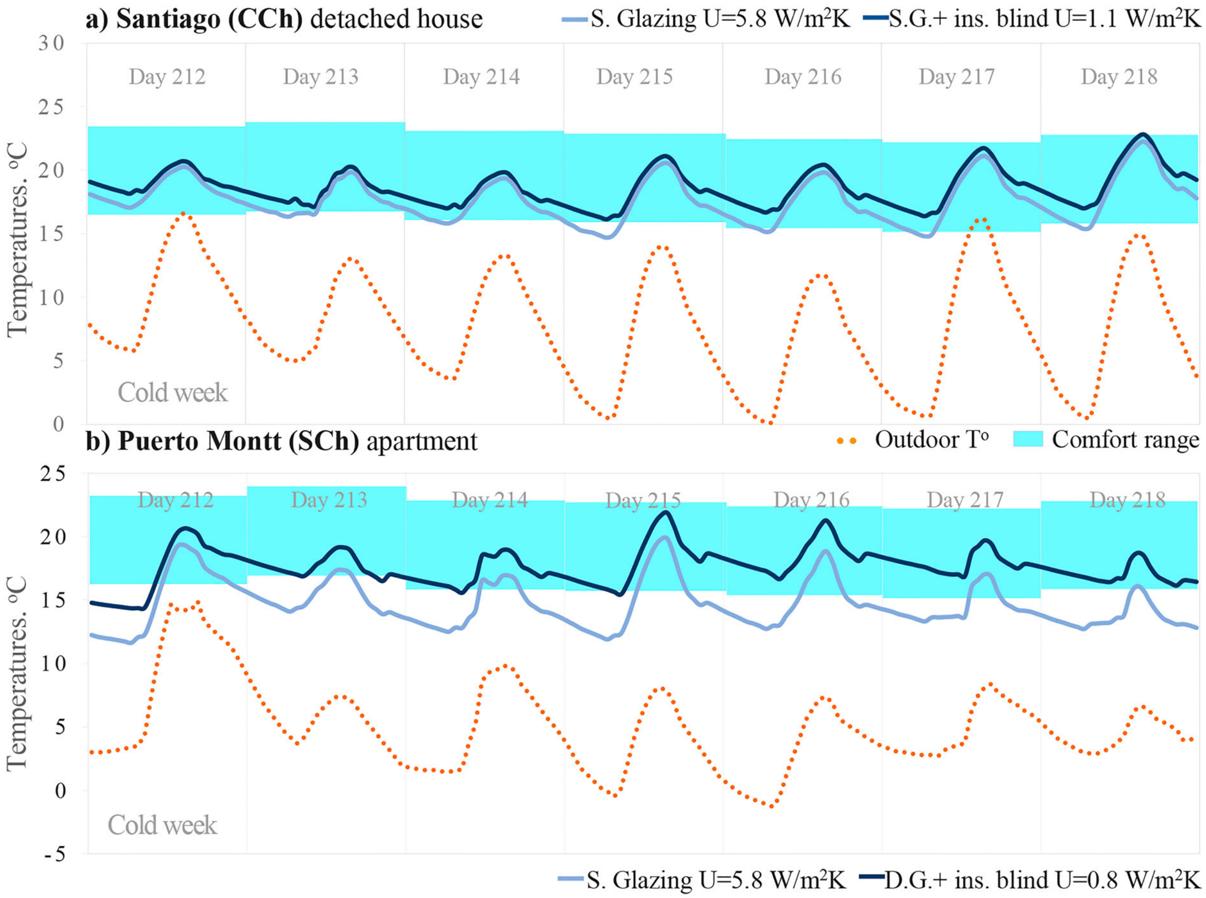

Figure A4. Effect of using insulated shutters.