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Application of adaptive comfort behaviors in Chilean social housing standards under the influence of climate change

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Abstract

Currently, energy performance indicators for buildings are associated with the primary energy source consumption, CO_2 emissions or net energy distribution, which together set the building's energy efficiency. The evaluation is frequently based on setpoint temperatures and hours of operation. However, these fixed parameters are not suitable for social housing simulation as their performance tends to be in free running, excluding extremely cold or warm conditions. Therefore, a more successful assessment for the efficiency of these buildings is the users' capability to live within adaptive comfort ranges without air conditioning systems. The aim of this research is to analyze new Chilean standards for sustainable social housing in the context of climate change using the adaptive comfort approach addressed in EN 15251:2007. Using EnergyPlus simulation software, 16 parametric series are analyzed for current conditions and validated against on-site measurements. Meanwhile, a prediction for the climate in 2050 has also been taken into account. The case study is the most widespread low cost dwelling model. The study demonstrates that the period of time within thermal comfort conditions varies substantially if analysis is done using the adaptive comfort standard or the Sustainable Construction Code (CCS) for Chilean housing. Considering climate change, the percentage of time fluctuates from −19.00% to 24.30%. Concluding that the adaptive comfort model has a greater capacity to positively assess indoor temperatures for social housing in Central-Southern Chile. This research also establishes that it is possible to provide homes where standards are improved within comfort conditions without using artificial means, 99.67% of the time currently and 88.89% in the future.

Keywords
social housing energy policy,
thermal performance,
climate change,
climate adaption,
adaptive comfort

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1 Introduction

Nowadays, the minimization of energy consumption, eradication of fuel poverty and mitigation of climate change are the main challenges of the building sector (Santamouris 2016), where buildings consume between 30% and 40% of the world's total energy (UNEP 2012). According to the International Energy Agency, this could increase to 38.4 PWh in 2040 (IEA 2013). Therefore, buildings' energy consumption and energy consumption per capita have ceased to be indicators of economic prosperity and social welfare (Nicol 2007).

The building's energy consumption is related to several factors such as location, envelope, internal loads, air conditioning and ventilation equipment, and at the same time, to the requirements of thermal comfort (Attia and Carlucci 2015). Those standards for thermal comfort help establishing the consumption or indoor temperature in a space under certain loads. Their proper definition is crucial to achieve comfort for future users and to reduce energy consumption (Nicol and Humphreys 2002).

Adaptive comfort models have been developed taking into account the natural tendency of people to adapt to the changing environmental conditions (Humphreys et al.

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2013). Unlike other comfort standards, the adaptive model allows for a wider range of temperatures. Humphreys suggested that it could be calculated for free running buildings using the following equation (Humphreys 1978):

$$T_{\mathrm{c}} = aT_{\mathrm{OUT}} + b \tag{1}$$

where T_{c} is the comfort temperature (°C), T_{OUT} is the outside temperature index (°C), and a and b are constants. Humphreys indicates that monthly outside temperature can be used to calculate the indoor comfort temperature index (McCartney and Nicol 2002).

Policies focused on rationalizing the energy use are becoming increasingly widespread due to the economic downturn and climate change (European Commission 2002, 2010). Hence, both constructive standards and thermal comfort requirements are developing in buildings. Some authors have demonstrated that applying adaptive comfort models could generate energy savings ranging from 10% to 18% in warm climates (Attia and Carlucci 2015). On the other hand, it is acknowledged that future predictions of energy consumption in cold climates might differ from the current state due to climate change (Chow 2012).

Current standards generally quantify energy efficiency on the basis of energy consumption or CO_2 emissions, as considered in EN 15603:2008 and EN 15217:2007 (CEN 2007a, 2008). Therefore, construction standards such as transmittance, ventilation, infiltration rates are established depending on their impact on the reduction of energy consumption (European Commission 2002, 2010).

The Building Research Establishment (BRE) together with the Ministry of Housing and Town Planning (MINVU) developed the Sustainable Construction Code (CCS) for social housing in Chile (Building Research Establishment 2016). The CCS is a guide whose focus is to improve energy efficiency and environmental performance in housing during the design, construction and operation stages. Its main goal is to develop higher sustainability technical standards for housing, taking into account the different geographical and climate conditions found in the different regions of Chile. The CCS looks to accelerate the transition towards quality homes that provide comfort for their occupants. These sustainable construction standards are set out to achieve low energy performance dwellings by 2050.

Currently, the complex interplay between climate change and thermal comfort models can play a key role regarding research and development in building science, hence different climate prediction and thermal acceptability models have been generated around the world. For the Chilean case, the CCS establishes that the passive design of dwellings must at least ensure that, 80% of the year, indoor temperatures are between 20 and 27 °C during the day and 17 and 27 °C at night, without applying any adaptive comfort concepts addressed in ASHRAE 55-2013 and EN 15251:2007 (ASHRAE 2013; CEN 2007b). These ranges though are far wider than usual standards. Again, for the Chilean case, taking the RITCH (Chilean standard for heating, ventilation, air conditioning and refrigeration) as a reference, which sets comfort within a strict range of 23–25 °C in summer and 20–22 °C in winter, it is remarkable how the CCS considers the adaptability of occupants as a potential scenario for reducing energy consumption.

This study aims to assess the necessary guidelines for designing passive social housing under the influence of the A2 greenhouse gases (GHG) climate scenario in the city of Concepción, the largest city in Central-South of Chile (Csb, according to the Koppen-Geiger classification). The most widespread social housing prototype was selected as a model for the analysis using dynamic thermal simulation. The yearly period when the building maintains comfort conditions was evaluated based on CCS and the adaptive comfort model established in EN 15251, for a current scenario and for the year 2050. The evaluation was conducted based on annual hours where the dwellings are in thermal comfort conditions when operating in free running, discussing the difference between applying static comfort ranges or the adaptive comfort model in accordance with EN 15251, for the current scenario and for 2050.

This paper is organized into six sections. Firstly, the background of the Chilean housing policy and the main objectives are identified. Secondly, the basics of adaptive thermal comfort are discussed. Thirdly, the influence of climate change on the area of study is assessed. The fourth section clarifies the methods and parameters used in the study. The fifth section carries out the parametric results of the case study, which considers the use of adaptive comfort model under a climate change scenario. The final section validates, discusses and concludes the main findings, implications and limitations.

2 Current Chilean social housing policy

From 1964 to 2015 more than 3.5 million households have received subsidies. This represents an approximate investment of USD 19,000 million since 1990 (MINVU 2016a). These figures point out that the Chilean government is concerned about the housing deficit and the quality of life of the most disadvantaged population. Housing subsidies addressed as SD-01 and SD-49 help families in homeownership (MINVU 2011a,b). Gross area for dwellings ranges from 36 m^2 to 55 m^2, and in most of cases they are isolated and rarely semi-detached, forming rows or organized in a block. The varying models from the Government's Housing and Urban Development Service's (SERVIU) housing repository of the Bío-Bío Region are depicted in Fig. 1 (MINVU 2016b). Such houses are built on only one level with three bedrooms, a living-dining room, kitchen and bathroom. The geometry is fairly standardized due to the limitations of the gross surface. Constructive characteristics are also standardized, based on lightweight construction systems resting on a concrete slab. Structural walls and the roof structure are usually made of wood. Exterior coatings are done in most cases with fiber-cement boards; inner lining is built with gypsum wallboard and the cover is done using corrugated zinc sheets. Openings are made of aluminum or PVC with simple glass. Due to their construction systems, they tend to be housing with a low degree of air tightness and a low thermal inertia (CITEC UBB; DECON UC 2012).

Historically speaking, building codes in Chile are not familiarized with energy efficiency. Currently, a mandatory thermal regulation is included in the General Ordinance of Urbanism and Constructions (Art. 4.1.10. OGUC) (Ministerio de vivienda y urbanismo (MINVU) 1992); alongside this, the Sustainable Construction Code (CCS) for housing can be observed, although it is not mandatory (Building Research Establishment 2016).

Nevertheless, it is necessary to indicate that the current standards are relatively low when compared to international standards (Table 1) (Kunkel et al. 2015). Because of this, even new buildings will have to be overhauled in a not so distant future (Bustamante et al. 2009). The same author has concluded that, despite the building sector accounting for 21.3% of the final energy consumption of the country, a large number of homes fall below the comfort temperature in winter because of the high price of fuel and the low income of their occupants. When considering the latter, most dwellings are in free running or just fall into mix mode; hence, adaptive comfort models are applicable. Thus, it is of capital importance that both existing and future buildings should move forward towards energy efficiency. This is especially true when one considers that even with the incorporation of these initiatives, the low thermal performance of these dwellings costs the Chilean government, approximately, USD 1000 million a year.

Additionally, there are other factors that need to be considered, such as negative effects on health and the productivity individuals have (Figueroa et al. 2013) as a result of living with inadequate thermal comfort conditions. This data is also supported by the Energy and Studies Program of the University of Chile (PRIEN), which estimates that the building sector will represent 18% of the national total potential for energy efficiency by 2020, only surpassed by the industrial and mining sector (Programa de Estudios e Investigaciones en Energía (PRIEN) 2008).

3 Evaluation index for adaptive thermal comfort

Nowadays, building energy performance indicators are associated with primary energy source consumption, CO_2 emissions or net energy distribution, which determine the

Fig. 1 Most extended social dwelling typologies according to SD-49

Table 1 Transmittance or *U* value, ventilation and air tightness limitations for Concepción. General Ordinance of Urbanism and Constructions (Art. 4.1.10. OGUC) vs Sustainable Construction Code (CCS)

Case	*U* openings (W/(m^2·K))			*U* envelope (W/(m^2·K))			Ventilation (L/(s·person))	Air tightness (ACH50)
	<21%	21%–60%	60%–75%	Roof	Wall	Floor ((m^2·K/W)×100)		
OGUC	>3.6	2.4–3.6	< 2.4	0.38	1.7	150	—	—
CCS	—	2.4–3.6	< 2.4	0.33	0.50	45	5.2	8

energy efficiency (CEN 2007a). EN 15603:2008, EN 15217:2007 standards and CCS are based on quantifiable parameters associated with energy consumption (Building Research Establishment 2016; CEN 2007a, 2008). Their evaluation is based on set point temperatures and hours of operation. Those fixed temperatures are not suitable for social housing simulations or indeed evaluation, since their performance tends to be in free running mode excluding extremely cold or warm conditions, where these could operate in mix mode. Therefore, a more successful assessment for the efficiency of these buildings would be the users' capability to be within adaptive comfort ranges, considering the percentage of time in which dwellings do not need air conditioning as an indicator.

The adaptive comfort model addressed in EN 15251:2007 has been developed from the SCATs project (Smart Control and Thermal Comfort), where information of naturally ventilated buildings and their occupants was established (CEN 2007b; McCartney and Nicol 2002; Nicol and Humphreys 2002). The application of this model is suitable for buildings that are mainly used for human occupation with sedentary activities with easy access to operable windows and where occupants can adapt their clothing to indoor thermal oscillation ranging from 0.5 to 1.0 clo (ISO 2007). With regard to the physical activity of the occupants, these activities must be almost completely sedentary, with metabolic activity levels between 1.0 and 1.3 met (ISO 2004).

For the application of this thermal comfort model, spaces must be equipped with operable windows which can be easily opened and adjusted by occupants. The building can operate in mix mode, if mechanical cooling is not used. Mechanical ventilation can be used, albeit the windows operation should be a preferred option to regulate indoor thermal conditions. In addition, there may be other methods for personal control of the indoor environment such as fans, shutters and night-time ventilation. Spaces can be equipped with a heating system, but the adaptive comfort model is applicable during times of the year in which the system is not operating (CEN 2007b). In the former case, fixed comfort temperatures are applied just as in the CCS. Although, it is considered that heating systems should be used when the prevailing mean outdoor air temperature obtained from Eq. (8) is lower than 15 °C.

Four comfort ranges are established in the standard as per the expectations, as well as other factors that influence comfort perception and building age (Table 2). Table 3 depicts the equations used for Categories I, II and III, which set the acceptable comfort limits in regard to prevailing mean outdoor air temperature (Eq. (8)). EN 15251 establishes the applicability of the lower limit from a range of the prevailing mean outdoor temperature as 15 °C to 30 °C, as well as the upper limit of 10 °C to 30 °C. When outside these limits, the comfort is considered static or dependent on different Eqs. (2)–(7), pursuant the standard (Table 3).

For the calculation of the prevailing mean outdoor air temperature θ_{rm} of a particular day, outside average temperatures of the previous 7 days are used, with $\theta_{\mathrm{ed}-1}$ being the daily outdoor average temperature of the previous day; $\theta_{\mathrm{ed}-2}$ the daily outdoor average temperature two days before, and so on; this is summed up in Eq. (8) (CEN 2007b). These daily average temperatures throughout the 365 days of the year are compared with the temperatures that are operative

Table 2 Expectation categories addressed in EN 15251:2007

Category	Detail
I	High level of expectation, recommended for spaces occupied by weak and sensitive people with special requirements, such as handicapped, sick, elderly and very young children
II	Normal level of expectation; should be used for new and renovated buildings
III	Acceptable and moderate level of expectation; It can be used in existing buildings
IV	Values outside of the criteria of the preceding categories. This category should only be accepted during a limited part of a year

Table 3 Comfort temperature ranges per category in regard to prevailing mean outdoor air temperature (θ_{rm}) EN 15251:2007

Category - limit		Prevailing mean outdoor air temperature θ_{rm} - comfort temperature			
		$\theta_{\mathrm{rm}} < 10$ °C	10 °C $\le \theta_{\mathrm{rm}} <$ 15 °C	15 °C $\le \theta_{\mathrm{rm}} \le$ 30 °C	$\theta_{\mathrm{rm}} >$ 30 °C
I	Upper comfort limit θ_{imax} (UI)	25.0	$0.33\times\theta_{\mathrm{rm}}+18.8+2$ (Eq. (2))	$0.33\times\theta_{\mathrm{rm}}+18.8+2$ (Eq. (2))	25.5
	Lower comfort limit θ_{imin} (LI)	21.0	21.0	$0.33\times\theta_{\mathrm{rm}}+18.8-2$ (Eq. (3))	23.5
II	Upper comfort limit θ_{imax} (UII)	25.0	$0.33\times\theta_{\mathrm{rm}}+18.8+3$ (Eq. (4))	$0.33\times\theta_{\mathrm{rm}}+18.8+3$ (Eq. (4))	26.0
	Lower comfort limit θ_{imin} (LII)	20.0	20.0	$0.33\times\theta_{\mathrm{rm}}+18.8-3$ (Eq. (5))	23.0
III	Upper comfort limit θ_{imax} (UIII)	25.0	$0.33\times\theta_{\mathrm{rm}}+18.8-4$ (Eq. (7))	$0.33\times\theta_{\mathrm{rm}}+18.8+4$ (Eq. (6))	27.0
	Lower comfort limit θ_{imin} (LIII)	18.0	18.0	$0.33\times\theta_{\mathrm{rm}}+18.8-4$ (Eq. (7))	22.0

during the 8760 hours of a year. Finally, they are assessed within the limits of the I and III categories.

$$\theta_{\mathrm{rm}} = (\theta_{\mathrm{ed}-1} + 0.8\times\theta_{\mathrm{ed}-2} + 0.6\times\theta_{\mathrm{ed}-3} + 0.5\times\theta_{\mathrm{ed}-4} + 0.4\times\theta_{\mathrm{ed}-5} + 0.3\times\theta_{\mathrm{ed}-6} + 0.2\times\theta_{\mathrm{ed}-7})/3.8 \qquad (8)$$

This adaptive thermal comfort model is applicable to social housing in the Central-South area of Chile since climate conditions and users economic particularities mean that dwellings are in free running with natural ventilation, using heating systems when the temperatures are very low (Bustamante et al. 2009).

4 Generation of the A2 greenhouse gas emission scenario

Predictions for future climate scenarios and their influence on the building industry are proposed as one of the fields of research and development for building science. Since the creation of the Intergovernmental Panel on Climate Change (IPCC) in 1988, which has recently published its Fifth Assessment Report (AR5) (Edenhofer et al. 2014; IPCC 2014), there are numerous studies that consider global warming, emissions increases, and the scarcity of natural resources. In this line, sundry prediction models have been generated for various climate scenarios (Jentsch et al. 2008). Most of these models have been developed in the United Kingdom (Mylona 2012), although they have increasingly extended throughout the international framework (Guan 2009; Jentsch et al. 2013). Currently, the IPCC, supported by the United Nations Environment Program (UNEP) and the World Meteorological Organization (WMO), which is the most recognized organization in this matter, envisages multiple emission scenarios for the near future (2020, 2050 and 2080) (IPCC 2014).

Future climate scenarios have been modelled using the UK Met Office Hadley Centre Coupled Model 3 HadCM3 (Met Office 2016). This model takes into account the combination of A2a, A2b and A2c scenarios regarding CO_2 emissions. Using the morphing tool CCWorldWeatherGen (Met Office 2016), based on the studies of Belcher et al. (Belcher et al. 2005), the EPW file of Concepción is "morphed" with the GHG A2 emissions scenario, obtaining sets of climate data for 2050 (Fig. 2)(Jentsch et al. 2013).

5 Methods

This methodology considers two key issues: the first is based on a comparison between the results of the CCS and the adaptive comfort model EN 15251:2007 (Building Research Establishment 2016; CEN 2007b). The second one is related to the strategies needed to increase the percentage of time where dwellings are within comfort limits. The main goal is to assess how long the considered social housing prototype will be able to function in free running. The applicability of adaptive comfort in the prototypes considered can be assessed by means of an improvement in the standards addressed in CCS, aiming at minimizing energy consumption.

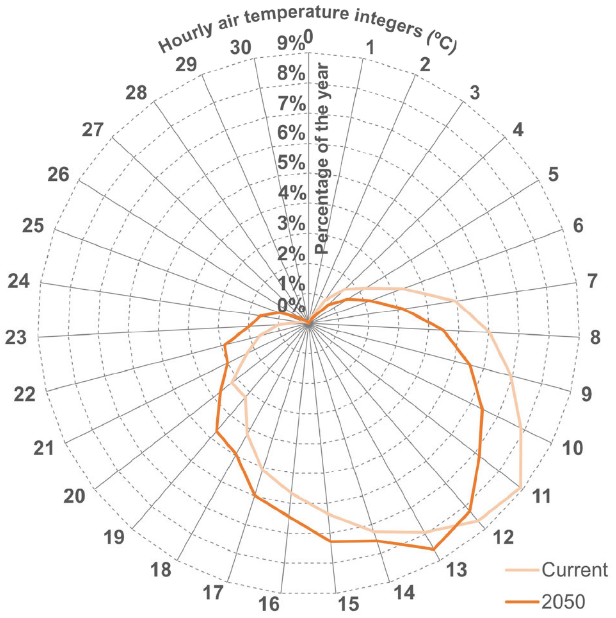

Fig. 2 Temperature distribution (current and 2050 (percentage of time))

Using the most widespread typology of social housing as prototypes (Fig. 3), parametric simulations have been made using EnergyPlus software. All of them are located in the city of Concepción. These prototypes have been extracted from the SERVIU database of the Bío-Bío region, with the chosen case-study being the most representative within the typologies of the housing repository (MINVU 2016b). It is an isolated dwelling with a greater exposed envelope that implies more unfavorable thermal performance (Pérez Fargallo et al. 2015, 2016).

The prototypes were parameterized according to their internal loads (Table 4), constructive features (Table 5) and occupancy schedule (Fig. 4). The main data that exert an influence on energy consumption were calculated considering the lowest construction cost for a building located in the climate zone of the study. These involve transmission features of the envelope, air flow, infiltration and thermal mass (ISO 2008). Occupation, lighting, equipment and ventilation schedules have been obtained from the CCS (Fig. 4). Combining all of them, 16 cases have been considered according to their transmittance, thermal mass, internal loads, ventilation, infiltration and usage profiles of the CCS for the climate zone of Concepción. These improvements were analyzed by means of 12 simple parameterization cases,

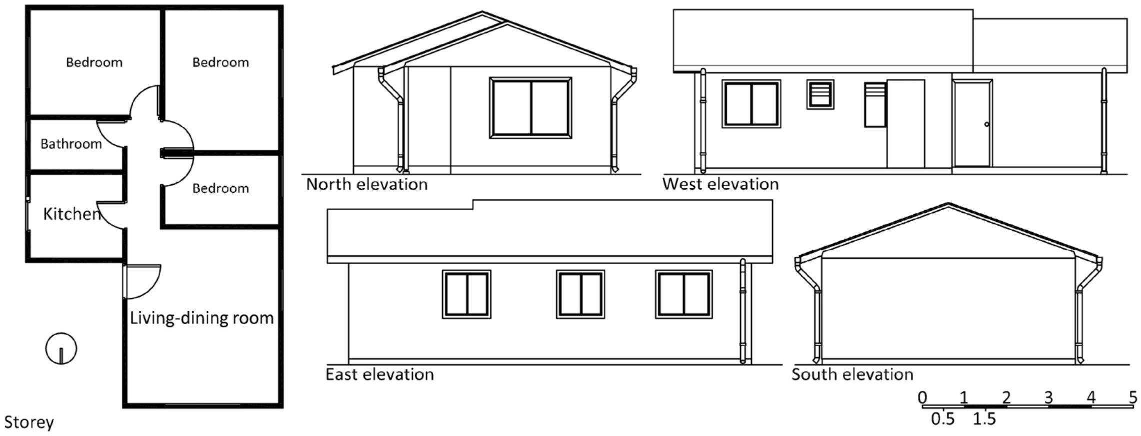

Fig. 3 Dwelling test model

Table 4 Internal heat loads for the models

	Living-dining room	Kitchen	Bedroom	Bathroom	Corridor
Illumination (W/m^2)	23	13	12	13	5
Occupation (W/m^2)	8.9	8.9	8.9	8.9	8.9
Equipment (W/m^2)	12.40	12.40	12.40	—	12.40

Table 5 Parameterization of the models

			U envelope (W/(m^2·K))			Ventilation (L/(s·person))[1]					
	Case	*U* openings (W/(m^2·K))	Roof	Wall	Slab ((m^2·K/W)×100)	Schedule	Very cold months	Cold months	Warmer months	Infiltration (ACH)	Special solutions
Base cases	0[2]	3.16	0.38	1.7	150	24 h	5.2	5.2	5.2	1	—
	1	3.16	0.33	0.50	45	24 h	5.2	5.2	5.2	1	—
	2	2.68	0.33	0.50	45	24 h	5.2	5.2	5.2	1	—
	3	1.94	0.33	0.50	45	24 h	5.2	5.2	5.2	1	—
	4	3.16	0.20	0.35	0.30	24 h	5.2	5.2	5.2	1	—
	5	3.16	0.13	0.18	0.15	24 h	5.2	5.2	5.2	1	—
	6	3.16	0.33	0.50	45	24 h	5.2	5.2	10	1	—
	7	3.16	0.33	0.50	45	24 h	3.5	3.5	10	1	—
	8	3.16	0.33	0.50	45	24 h	2.0	3.5	10	1	—
	9	3.16	0.33	0.50	45	ON-OFF	2.0	3.5	10	1	—
	10	3.16	0.33	0.50	45	24 h	5.2	5.2	5.2	0.35	—
	11	3.16	0.33	0.50	45	24 h	5.2	5.2	5.2	1	Roof absorptivity 0.9
	12	3.16	0.33	0.50	45	24 h	5.2	5.2	5.2	1	Δ Thermal mass
Combination	13	3.16	0.33	0.50	45	24 h	2.0	3.5	10	0.35	—
	14	3.16	0.13	0.18	0.15	ON-OFF	2.0	3.5	10	0.35	—
	15	3.16	0.13	0.18	0.15	ON-OFF	2.0	3.5	10	0.35	Δ Thermal mass
	16	3.16	0.33	0.50	45	ON-OFF	2.0	3.5	10	0.35	—

[1] Warmer months: January, February, March, November and December. Cold months: April, September and October. Very cold months: May, June, July and August.

[2] Case 0 is created to validate the model.

considered both at the present time and in 2050. Thanks to these outcomes, 4 additional prototypes (cases 13 to 16) were assembled by combining the best simple cases.

The hypothesis for ventilation regarding cases 9, 14, 15 and 16 is established pursuant the usage schedules (Fig. 4). This hourly schedule is related to the climate variations, making a difference amongst warmer, cold and very cold months. Finally, the results have been discussed in order to

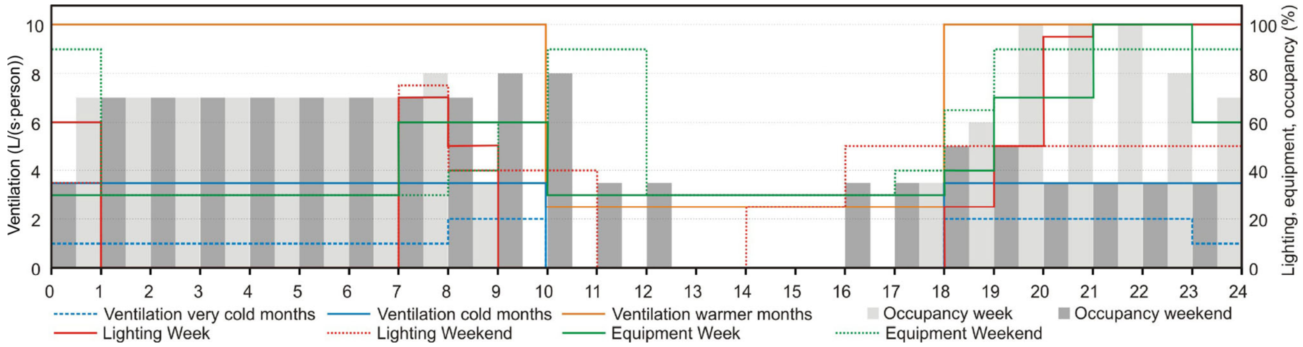

Fig. 4 Occupation, lighting and equipment and ventilation schedules

prioritize areas where social housing construction standards could effectively be improved, taking as a base the amount of time when the dwelling may function under free running conditions.

The parametric analysis cases which achieve better results have been selected to be combined. Transversely, it was decided to use cases 8 and 10 as the basis for all combinations. The choice of base case 8 was as this achieved the best results in the current and 2050 analyses of ventilation without applying the ON-OFF condition, while base case 10 was chosen as it assumed a relatively high improvement currently and was related to 8 by the regulation of heat losses in ventilation.

As a result, case 13 has been created by combining cases 8 and 10. Meanwhile, case 14 is a combination of cases 5, 8, 9 and 10; case 5 has been incorporated by assuming an improvement in housing thermal behavior at the current time, despite seeing a small reduction of comfort in 2050; finally, case 9 is composed by drastically reducing both discomfort conditions today and in the future just by an adequate arrangement of the schedule and the ventilation calendar.

Case 15 has been formed by cases 12 and 14, where it is seen that the thermal mass of the building is increased. This improvement, despite assuming a reduction of thermal comfort currently, will have a relatively high importance in the future scenario to contain the temperature rise due to climate change. Case 16 has been assembled from case 13 combining the ON-OFF schedule of Fig. 4. The aim of case 16 is to analyze the impact of a proper ventilation flow with a low air-tightness and a use ventilation profile, which is more appropriate to the period of the year and the schedule.

The numerical simulation model used to generate indoor operative temperatures (Ta) is the one considered by the EnergyPlus software. The data from temperatures are obtained and then assessed in Excel considering the standard EN 15251, with Eqs. (2), (3), (4), (5), (6), (7) and (8) to calculate the percentage of hours where the following criteria are met:

– Hot if: Upper comfort limit Category III (UIII) < Ta.
– Warm if: Upper comfort limit Category III (UIII) ≥ Ta > Upper comfort limit Category II (UII).
– Slightly warm if: Upper comfort limit Category II (UII) ≥ Ta > Upper comfort limit Category I (UI).
– Comfort if: Upper comfort limit Category I (UI) ≥ Ta ≥ Lower comfort limit Category I (LI)
– Slightly cool if: Lower comfort limit Category I (LI) > Ta ≥ Lower comfort limit Category II (LII).
– Cool if: Lower comfort limit Category II (LII) > Ta ≥ Lower comfort limit Category III (LIII).
– Cold if: Lower comfort limit Category III > Ta.
– EN 15251* (Total comfort) Upper comfort limit Category III (UIII) ≥ Ta ≥ Lower comfort limit Category III (LIII).

In order to make the analysis clearer for the reader, a distinction has been made depending on the different categories. Firstly, it has been considered that indoor space is in "comfort" when the range of operative temperatures is within the range of Eqs. (2) and (3) (Category I). Secondly, a space is "slightly cool" or "slightly warm" when its operative temperature falls within Eqs. (4) and (5) (Category II). Thirdly, if a room is between Eqs. (6) and (7) (Category III) it is "cool" or "warm". Finally, if the indoor operative temperatures are below or above Category III, the space is "cold" or "warm", respectively. It is necessary to clarify that Category III is an "acceptable and moderate level of expectation" and it can be used in existing buildings, therefore it is possible to determine that it is still a comfortable environment. Consequently, in the "Total Comfort" evaluation represented as per EN 15251*, the ranges of Category III are depicted.

6 Discussion and results

6.1 Model validation

The simulation model has been validated pursuant ASHRAE Guideline 14 (ANSI/ASHRAE 2014), which is one of the most widespread validation processes (Royapoor and Roskilly 2015). According to this guideline, hourly temperature data should at least be used for validation, and the model is considered validated if it has Mean Bias Error (MBE) that is not larger than 10%, and the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) is not greater than 30%. In this case, the validation was carried out by means of comparing simulated and measured dry bulb temperature data, taken from both internal and external sensors every 10 minutes, thus exceeding the ASHRAE recommendations (every hour).

During year 2016, 6 houses, whose typology and constructive systems are similar to those considered in the simulated case, were monitored. Dry bulb temperature (DBT) and RH sensors, which took measures every 10 minutes, were installed in the living rooms of the dwellings. The houses were randomly monitored over 7-day-long periods, between 2016 April 4th and 2016 November 11th, giving as a result 910 hours of monitoring, approximately 10.4% of the total hours of 2016. Conjointly, exterior DBT was monitored by a meteorological station located in the campus of the University of Bío-Bío during the same year.

In this case, MBE is 3.48% indoors and 7.58% outdoors (Table 6), with both values falling below the 10% recommendation for hourly comparisons. CV(RMSE) is also below 30%, both for indoors (13.19%) and outdoors (13.76%). Thus, the base case model is validated in order to carry out the different hypotheses for CCS cases in the current and 2050 scenarios.

6.2 Comfort in social housing: present scenario

Thermal comfort can be assessed by different models. The Chilean standard CCS establishes that comfort temperatures for the Central-South area, where Concepción is located, must be between 20 and 27 °C during the day and between 17 and 27 °C during the night (Building Research Establishment 2016). However, EN 15215:2007 sets four comfort temperature ranges depending on the outdoor temperature. The proposed assessment has considered that the building is within acceptable comfort levels when Category III is applied, considering the ranges for Categories I and II (CEN 2007b). Hence, such values could be considered comfortable enough so that HVAC is not necessary. Values outside those limits are considered as discomfort.

Table 6 Model validation

	Internal		External	
	Simulation	Monitoring	Simulation	Monitoring
Average temp. (°C)	16.33	16.82	12.28	13.20
Sum of temp. (°C)	14,866.72	15,403.30	95,592.13	101,962.75
Sum of the differences (°C)	536.57 °C		7732.73 °C	
MBE (%)	3.48		7.58	
RMSE	2.22		1.82	
CV(RMSE) (%)	13.19		13.76	

In order to compare the comfort standards addressed in the CCS with those ones from EN 15215:2007 without the use of HVAC, a free running model was simulated (case 1) (Fig. 5). It is remarkable that the comfort defined by CCS, which might be called a "static" model, has a wider range of temperatures than the adaptive comfort model EN 15251:2007, being 7 °C during the day and 10 °C at night. Whereas, the adaptive model has a daily range of 8 °C (Category III), 6 °C for Category II and 4 °C for Category I. However, the latter limits are not constant and they adapt according to outdoor temperatures (Fig. 5). This shows that the adaptive comfort model better adapts to the thermal performance of social housing under free running (Attia and Carlucci 2015; CEN 2007b).

Considering the climate of Concepción, the results show

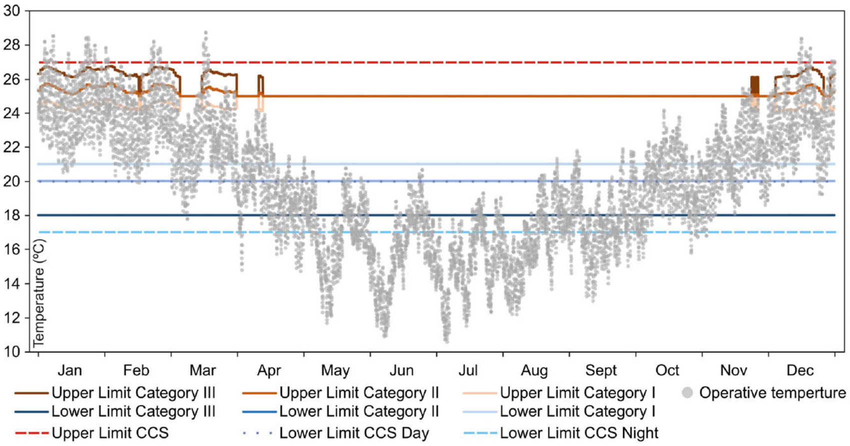

Fig. 5 Operative temperature and average outdoor air temperature with regard to the limits addressed in CCS and EN 15251:2007 (case 1, present scenario)

that discomfort is mainly associated with low temperatures, which are near 10 °C during the cold and very cold months, from mid-April to September. During the warmer months, despite overheating being present, its effect is not remarkable. Therefore, those improvements observed in the CCS standard are mainly related with the building performance during the cold season, but several measures should be also envisaged regarding comfort during summer (Table 7).

Figure 6 depicts that the static comfort model (CCS), despite having wider temperature ranges, gives worse results than the adaptive model, which is far more accurate. The case 1 test model would be within comfort 47.47% of the time, according to the CCS standard. However, if the adaptive model is considered, the dwelling would be within comfort (Category I) during 28.29% of the time; slightly cool (7.75%), slightly warm (5.19%), cool (16.37%) and warm (3.41%). As until Category III is considered as acceptable comfort levels (EN 15251*), the total amount of comfort

Table 7 Percentage of time in different environmental situations under adaptive comfort model approach to present time and in 2050

Case	Hot UIII < Ta	Warm UIII ≥ Ta > UII	Slightly warm UII ≥ Ta > UI	Comfort UI ≥ Ta ≥ LI	Slightly cool LI > Ta ≥ LII	Cool LII > Ta ≥ LIII	Cold LIII > Ta	Total comfort[1] UIII ≥ Ta ≥ LIII	Dif base
Current									
1	3.05	3.41	5.19	28.29	7.75	16.37	35.94	61.02	—
2	1.78	2.79	5.07	28.12	7.95	17.04	37.26	60.96	−0.06
3	1.62	2.89	4.94	28.28	8.05	17.08	37.15	61.23	0.22
4	4.52	4.54	6.60	28.61	7.90	18.08	29.75	65.73	4.71
5	6.47	6.23	8.03	26.61	8.04	18.50	26.12	67.41	6.39
6	0.55	1.56	2.96	29.03	11.66	22.84	31.40	68.05	7.03
7	0.58	1.66	3.07	29.91	12.01	23.09	29.68	69.74	8.72
8	0.58	1.66	3.07	30.73	12.49	24.89	26.59	72.83	11.82
9	1.14	2.11	4.41	32.60	12.44	24.66	22.64	76.22	15.21
10	7.51	5.30	6.13	28.57	7.83	18.32	26.34	66.15	5.14
11	4.67	4.33	4.94	27.90	7.50	16.38	34.28	61.05	0.03
12	0.00	0.91	5.66	31.26	7.00	14.46	40.71	59.29	−1.72
13	1.56	2.50	4.37	38.37	14.16	23.25	15.79	82.65	21.63
14	9.89	6.26	7.73	55.42	10.35	9.09	1.27	88.85	27.83
15	0.25	4.86	10.26	49.25	15.27	20.02	0.08	99.67	38.65
16	2.75	3.42	5.05	39.81	13.90	22.15	12.92	84.33	23.31
2050									
1	9.99	6.76	7.45	28.46	8.05	18.46	20.83	69.18	—
2	7.81	6.64	7.69	28.86	8.21	18.97	21.82	70.38	1.20
3	7.66	6.75	7.68	28.89	8.28	19.09	21.66	70.68	1.51
4	13.71	8.33	8.05	27.12	9.22	16.92	16.64	69.65	0.47
5	19.00	8.64	7.53	25.56	9.57	16.60	13.11	67.90	−1.28
6	3.86	4.76	6.34	34.33	9.71	19.97	21.04	75.10	5.92
7	4.08	4.87	6.50	37.90	11.07	18.81	16.77	79.16	9.98
8	4.08	4.87	6.50	40.13	12.48	18.89	13.06	82.87	13.69
9	5.97	6.02	6.70	41.30	12.01	17.65	10.35	83.68	14.50
10	16.55	7.89	7.34	27.82	9.28	16.21	14.91	68.54	−0.64
11	12.74	6.72	7.20	27.75	7.81	17.73	20.05	67.21	−1.96
12	2.20	8.42	12.24	26.07	7.33	19.50	24.24	73.56	4.38
13	7.72	6.47	7.32	46.96	10.57	14.79	6.16	86.12	16.94
14	29.47	9.28	7.64	46.32	4.42	2.87	0.00	70.53	1.35
15	11.11	12.10	12.85	51.27	11.05	1.62	0.00	88.89	19.71
16	12.34	6.71	7.03	47.83	10.71	11.56	3.81	83.85	14.67

[1] (Total comfort) Lower comfort limit Category III (7) < Ta ≤ Upper comfort limit Category III (6).

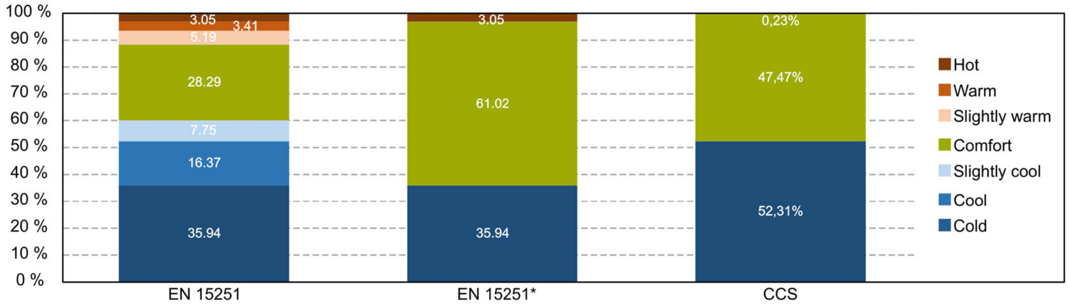

Fig. 6 Percentage of comfort conditions according to the CCS model and EN 15251:2007 (case 1, present scenario) (EN 15251*; (Total comfort) Lower comfort limit Category III (7) < Ta ≤ Upper comfort limit Category III (6))

using the adaptive comfort model spans 61.02% of the time, hence cooling systems are not a must. With regard to discomfort conditions, the adaptive model shows lower figures (38.98%) than the static model. Overheating, that is, warm conditions, is observed for just 0.23% of the time for the static model, whereas on using the adaptive model, this percentage rises to 3.05 % of the year.

The CCS states that a building can run without the use of HVAC system if it is able to maintain comfort conditions for at least 80% of the year. In order to achieve this percentage it would be necessary to increase the time span for comfort to 32.53% with regard to the CCS standard and 18.98% for EN 15251:2007. It is remarkable that the application of the adaptive model is able to foster the potential of the building to run in free oscillation during most of the year.

6.3 Impact of climate change in comfort conditions

Climate change can have different consequences on buildings' energy performance based on multiple factors. In the case of the city of Concepción, which is characterized by cold winters and mild summers, the application of the A2 GHG climate scenario improves significantly under winter conditions, whereas worse building performance can be expected in summer.

A change in climate conditions will exert a remarkable influence on the comfort levels (case 1) (Fig. 7), which will be displaced towards the warm zone. The simulations show higher indoor temperatures during the cold season (April–September) and also an increase in the number of hours when conditions will exceed the comfort limit on the warm side is observed for both of the models. As a consequence, it is expected that those strategies envisaged by the CCS to improve thermal comfort currently may not be feasible in the future.

The distribution of comfort levels will also be altered as a consequence of the change in climate conditions (Fig. 8). For both models, the distribution of thermal comfort will be shifted, increasing the time within comfort conditions by 9.31% for the CCS model and 8.16% for the total acceptable comfort levels (EN 15251*) of the adaptive model. This time span is basically subtracted from the discomfort during cold hours, by 13.02% and 15.11%, respectively. On the other hand, discomfort associated with warm conditions is increased,

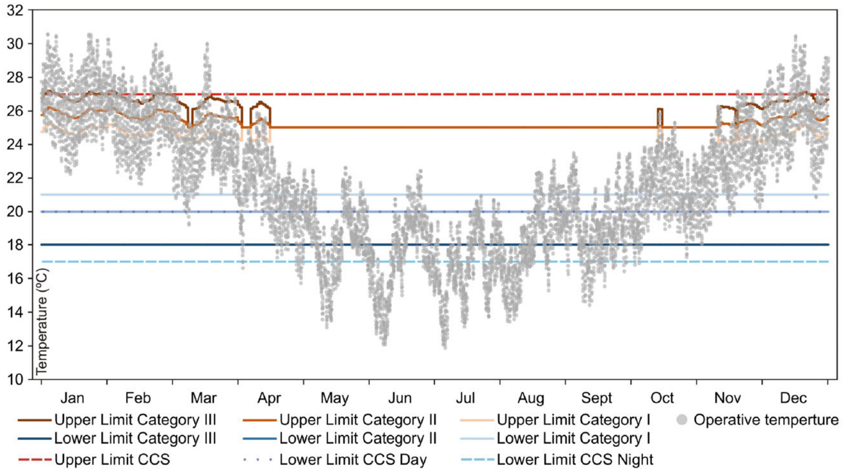

Fig. 7 Operative temperature and average outdoor air temperatures in relation to the limits addressed in CCS and EN 15251:2007 (case 1, year 2050)

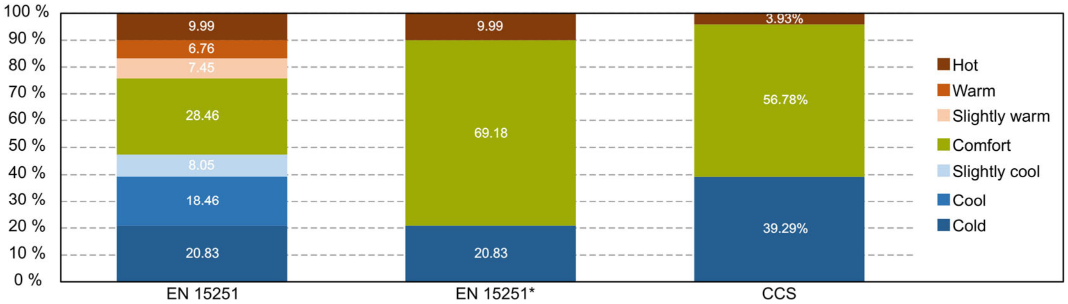

Fig. 8 Percentage of comfort conditions according to the CCS standard and EN 15251:2007 (case 1, year 2050) (EN 15251*; (Total comfort) Lower comfort limit Category III (7) < Ta ≤ Upper comfort limit Category III (6))

being, for the latter, 3.70% for the CCS standard and 6.94% for the adaptive model. Considering the adaptive model per category, the dwelling would be within comfort (Category I) during 28.46% of the time; slightly cool (8.05%), slightly warm (7.45%), cool (18.46%) and warm (6.76%).

Given these facts, it can be stated that those strategies proposed currently will not be compatible in most cases with the future needs, due to a temperature increase and the appearance of overheating in dwellings. As a result of the former, it is possible to assure that the strategies proposed for the present are incompatible in most cases with future needs due to the increase in temperatures. Therefore, the assessment of the proposed improvements has been applied in both scenarios taking this situation into account.

6.4 Sustainable housing analysis

An iterative process has been followed in order to find the best adaptation strategy for the considered social housing prototype in a context of a climate change, comparing the situation currently with 2050. This continues to be important as the expected lifespan of these dwellings should be, at least, 30 years.

The CCS standard establishes basic requirements for sustainable housing construction, defining the following limitations for each climate zone: transmittance, thermal mass, internal loads, ventilation, infiltration and profiles time to use. Hence, first of all, a model complying with these basic requirements (case 1) was analyzed in order to identify potential problems regarding thermal comfort, at the current time and in 2050.

Cases 2 and 3 foresee changes in the thermal transmittance coefficient of the windows due to a change in the Window to Wall percentage. They consider a reduction in the transmittance of the glass surfaces, including 6/12/6 PVC frames and insulating glass; model 3 also considers low-emissivity glass.

Cases 4 and 5 implement stricter values for the thermal envelope (walls, roofs and slabs).

Cases 6, 7 and 8 maintain the original constructive configuration of case 1 but modify the rate of ventilation accordingly for each one of the defined periods. Case 6 implements a higher rate of ventilation for the warm period; cases 7 and 8 maintain the rate of ventilation of case 6 and add a decrease in the rate during the cool and cold period.

Case 10 reduces the infiltration rate from 1 to 0.35.

Cases 11 and 12 foresee special solutions not envisaged by the CCS standard. Case 11 simulates the behavior of the dwelling in the event that a roof material with high absorptivity would be installed. Finally, case 12 implements an envelope with a higher thermal mass.

The analysis of the results for these 12 base cases reveals that some modifications have a larger impact on comfort conditions than others (Table 7), in spite that the outcomes may be negligible or even negative in some scenarios. In addition, the outcome of this analysis is undertaken on the following basis of their impact on comfort at the present time and in 2050; while the properly assessed modifications set the basis for further research, which is undertaken in cases 13–16.

Cases 2 and 3 have a controversial effect. Despite improving the specs of windows, the number of hours in comfort stays nearly the same both at the present time and also in 2050, increasing only a mere 4.71% at most. Due to the very limited impact of these improvements, cases 2 and 3 were discarded for the simulation of cases 13–16.

An improved insulation (cases 4 and 5) results in a positive influence currently, 4.71% and 6.39% respectively. However, this effect is counteracted by the change in climate conditions by 2050, with ensuing negligible variations in comfort conditions. As a result, it can be stated that improvements in thermal transmittance are effective currently but not in a future scenario with higher temperatures, with the fact that higher insulation will result in more discomfort in the future also being remarkable.

Results regarding changes in the rate of ventilation (cases 6, 7 and 8) are clear. Increases in ventilation during the warmer months have a beneficial effect both at the present time (up to +11.82%) and in 2050 (up to +13.68%); going further in depth in this aspect, reducing ventilation during the cool and the cold period improves these figures, +8.72% and +9.98%, respectively; finally, adapting the rate for every period, that is, case 8, gives the best outcomes, +11.82% and +13.68%, respectively.

Taking the results from case 8, case 9 implements an improved adaptive ventilation schedule (Fig. 4), in contrast with a fixed 24h schedule. As a result, comfort is improved by 15.21% at the present time and by 14.50% in 2050.

Case 10 alters the infiltration rate. In this regard, it has to be noted that despite the CCS standard stating that airtightness at 50 Pa for the climate zone of the study should be less than 8 ACH50, the same document recommends a value of 1 ACH when carrying out dynamic simulations, with the latter being closer to international standards. Hence, case 10 includes a reduction in the airtightness from 1 to 0.35 ACH, giving as a result an increase of 5.14% in comfort at the present time, but a decrease of 0.64% at 2050, which can be considered null.

Cases 11 and 12 both implement passive features related to the thermal performance of the envelope, the former enhancing solar gains by the impinging radiation and the latter using thermal mass in order to boost heat storage capacity and thermal dampening of the building skin. Case 11 has negligible figures currently (+0.03%) and a decrease in 2050 (−1.96%); while case 12, on the contrary has poor results currently (−1.72%) and fairly good in 2050 (+4.38%). Nevertheless, it is remarkable how case 12 can achieve such a good comfort percentage in 2050 (73.56%), which means that, under the A2 climate scenario, thermal mass could place the dwelling close to the threshold value of 80%, necessary to dispense with HVAC systems. Despite a thermal mass of at least 0–70 kJ/(m²·K) being mandatory under the current CCS standard, it was considered appropriate to provide the building with at least 200–400 kJ/(m²·K) for the forthcoming climate scenario in 2050.

Gathering the best results from cases 1–12, four more cases have been compiled and simulated. Case 13 considers the improved ventilation rate from case 8 plus lower infiltration rate from case 10. Case 14 adds the optimized ventilation schedule from case 9 and also the improved *U* values from case 5. Case 15 takes as a base the former, but includes the improved thermal mass of case 12. Finally, case 16 features the same parameters as case 13 plus the improved ventilation schedule that was applied in case 9.

These four models offer remarkably improved results when being compared to the former base cases. First, all of them would be in comfort for more than 80% of the time, with the case 14 in 2050 being an exception with 70.53%. Even this figure, though it does not comply with the CCS criteria, can be considered fairly good in terms of passive design.

Going into a more in-depth discussion, it can be said that all models clearly improve the base case. Under the current scenario, these improvements are all above 20%; in 2050, the figures though are not so favorable, ranging from around 16.94% to 19.71%, with case 14 again being the one offering the least improvement, only 1.35%. The best option would be case 15, which shows remarkable figures: an improvement of 38.65% at the current time and 19.71% in 2050. Between those two extremes, cases 13 and 16 offer similar figures with favorable results both at the current time and in 2050.

Case 15 is the most promising with regard to adaptive comfort and more detailed analysis has been conducted in order to clarify until what extent fostering passive design would result in an amelioration of comfort conditions inside the house. Figure 9 depicts operative temperature versus the prevailing average outdoor temperature for this case. Limit

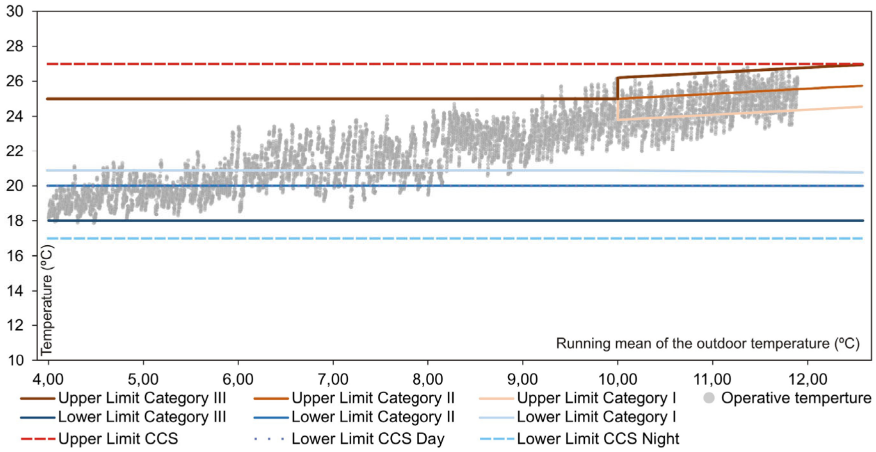

Fig. 9 Operative temperature and prevailing mean outdoor air temperature scatter plot in case 15 related to the limits addressed in CCS and EN 15251:2007 at the current time

values for Categories I and III (EN 15251:2007), as well as for the CCS, which makes a distinction between day and night, have been also plotted. In that way, the number of hours when temperatures are inside the ranges can be assessed.

Model 15 (Fig. 9) is within the limit for category III all year-round, with only 29 hours outside the boundaries. If Categories I and II are considered, limits are stricter, so the number of hours in discomfort also rises. If the CCS standard is enforced, more flexible conditions apply and, in consequence, the number of hours in comfort also increases.

When considering the same parameters in 2050, conditions change. As a consequence of the rise in average temperatures due to the application of the A2 scenario, the point cloud is displaced upwards in the plot, hence discomfort associated with warm conditions is present. The hours in discomfort during 1 whole year would be 973, that is, 11.11% of the year's total. In spite of this, the number of hours in comfort per the Category I standard is 51.27%, 12.85% of the time correspond to the "slightly warm" condition and 12.10% correspond to warm, all within acceptable comfort limits (Table 7, Fig. 10).

7 Conclusions

This research aims at clarifying how housing standards can help to foster adaptive comfort, both at the current time and in the future. In regard to this, the following outcomes can be outlined in relation with the case-study considered.

In climates characterized by cold winters and mild summers, such as the one taken into account in this study, an improvement in construction standards should be put under careful consideration, because higher benchmarks do not automatically imply higher levels of comfort. In this case, this approach, consisting on improving the specs of both the opaque and the transparent thermal envelope would have either null or even controversial effects. Instead of that, it has been demonstrated that occupant behavior plays a fundamental role when managing to obtain comfort, varying ventilation rates and adapting their thermal tolerance when the interaction between outdoor temperature and operative temperature make it possible. The best results would be achieved when combining both of them. Hence, it is can be stated that it is necessary to increase the requirements associated with the transmittance, ventilation, infiltrations and thermal mass of the Sustainable Construction Code, but only until certain limits and without forgetting that the interplay with the occupant's behavior should not be discarded. In other words, mild climates do not cope with the concept of high-spec, air-sealed and completely insulated social dwellings, but with an acceptable standard of construction combined with acceptable rates of ventilation, entailing occupants interplay as a must.

In this regard, case 15 has shown the most promising results. If the objective is achieving a comfortable and low-energy social dwelling, constructive specs should focus on improving the thermal mass of the envelope and also the conductivity up to certain values. Besides this, reducing infiltration rates and implementing an improved ventilation schedule, with adaptation to the cold and warm seasons, remains the key to fostering comfort through the application of the adaptive comfort model. This combination has shown the best balance between current and future scenarios (2050). Once again, this remains crucial as the life-span of building can reach an average of 30 years, with some of them being used for 40 or even 50 years.

Focusing on an international context, a comparative analysis of the comfort requirements of the Chilean CCS and the adaptive comfort model of EN 15251:2007 was done. It was pointed out that the adaptive comfort model has greater capacity to positively assess the indoor housing

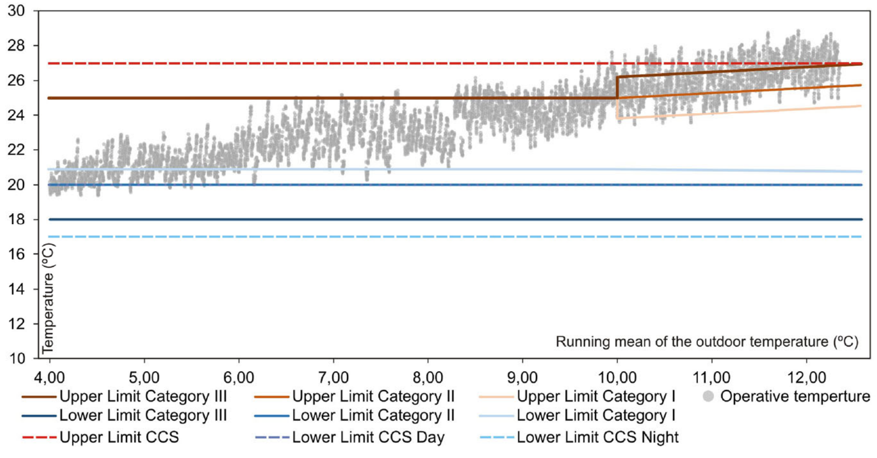

Fig. 10 Operative temperature and prevailing mean outdoor air temperature scatter plot in case 15 related to the limits addressed in CCS and EN 15251:2007 in 2050

temperatures when there are no HVAC systems, making a more accurate distinction between all different comfort categories. This fact indicates two remarkable conclusions. First, the static model is not suitable to evaluate the potential of a building to operate in free running, with an adaptive comfort approach being more suitable to these specific cases. Second, the international standards can be successfully applied to a concrete national scenario by comparing and assessing their requirements and, therefore, implementing the necessary adaptations. In this regard, the proposed model, based on parametric simulations run in the EnergyPlus software, has also been successfully validated against on-site measurements complying with ASHRAE Guideline 14.

The research has also found evidence that, in addition to the energy performance indicators associated with the primary energy source consumption, CO_2 emissions or net energy distribution, it is possible to use other indicators to evaluate the performance of a dwelling, especially in the case of social dwellings. Instead of looking solely at the energy consumption, the percentage of hours when the house can operate in free running within comfort limits has been proven to be a good indicator in order to devise a strategy to improve the constructive standard of these buildings. Good living conditions can be achieved in social dwellings with null or very low HVAC consumption.

This case study is focused on the city of Concepcion, but the methodology has the potential to be replicated in many densely-populated locations with similar climates. In that way, this research will lead to the development of energy policies, aimed at improving the thermal comfort in social housing considering the adaptive comfort approach and the temporal evolution of environmental variables due to global warming.

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