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Influence of Adaptive Comfort Models on Energy Improvement for Housing in Cold Areas

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Abstract: The evaluation of construction standards using adaptive thermal comfort models has a great impact on energy consumption. The analysis of a user's climate adaptation must be one of the first steps in the search for nearly/net Zero Energy Buildings (nZEB). The goal of this work is to analyze the standards recommended by the Chile's Construction with Sustainability Criteria for the building of housing, applying the ASHRAE 55-2017 and EN 15251:2007 adaptive comfort models in social housing. The study produces concrete recommendations associated with construction strategies, to increase the number of hours the user finds themselves with acceptable thermal comfort levels, without repercussions for energy consumption. Sixteen parametric series were evaluated with a dynamic simulation of the most common prototype of social housing in the Bio-Bio Region. The study shows that thermal comfort conditions can be increased through a combination of improvement measures compared to the ECCS standard (Construction Standards with Sustainability Criteria): 27.52% in the case of applying EN 15251:2007 and 24.04% in the case of ASHRAE 55-2017.

Keywords: climate adaptation; social housing; thermal comfort; adaptive comfort

1. Introduction

Buildings consume between 30% and 40% of the world's energy [1]. According to the International Energy Agency this could increase to 38.4 PWh by 2040 [2]. For this reason, energy consumption in buildings and energy consumption per capita are no longer indicators of economic prosperity and social well-being [3]. Currently, there is a combination of non-renewable energy resource depletion and global warming; therefore more energy efficient building development based on the use of renewable energy is being demanded [4]. The economic slowdown and climate change have forced those who are politically and scientifically responsible to rationalize the use of energy across the entire world [5,6], tending ever more towards drastically reducing energy consumption via so-called nearly/new Zero Energy Buildings (nZEB) [7–9]. The University of Chile's Studies and Energy Program (PRIEN in Spanish), estimated that the building sector will represent 18% of the total national energy efficiency potential for 2020, surpassed only by the industrial and mining sectors [10].

Energy consumption of buildings is associated with multiple factors, with the user's thermal indoor comfort demands standing out. An unsuitable internal temperature can mean either users are uncomfortable or that energy consumption increases. Thus, the building's sustainability level (i.e., minimal energy consumption) can be greatly impacted by this parameter if it is not suitable [11]. The adaptive comfort models are based on the natural tendency of individuals to adapt their thermoregulation, clothing, metabolic rate and psychological conditions to the changing conditions of the outdoor climate under natural ventilation conditions [12]. Unlike other comfort standards, this allows a greater range of temperatures related to the outside temperatures of the previous days.

In addition, the use of active air-conditioning systems in homes is subject to discussion [13] due to the increasing demand of energy resources in a scenario of expensive energy and energy poverty being more and more of a reality [14]. This is why a large number of current studies in the field of climate adaptation of the residential sector focus on the comfort study of their occupants, trying to reduce the use of active devices and intensifying passive strategies [15,16]. As an example of this, Attia has shown that the use of adaptive comfort models can generate energy savings of between 10% and 18% in warm climates [7].

The Chilean standard Construction Standards with Sustainability Criteria (ECCS by its Spanish acronym) for homes was made by the Building Research Establishment (BRE) along with the Executive Secretary of Sustainable Construction of the Chilean Housing and Urbanism Ministry (MINVU) [17]. The ECCS consists of technical guides aimed at establishing standards and best practices for the design, construction and operation of houses, both new or extant, with the goal of improving their environmental, economic and social performances, through the definition and incorporation of sustainability criteria, based on objective and verifiable parameters [17]. Technical "sustainability" standards have been developed for the housing industry, bearing in mind the different geographical and climatic situations of Chile. Its mission is to accelerate the transition of a residential building stock with low energy performance to one with improved comfort standards. The ECCS has established that the passive thermal design of homes must guarantee that between 60% and 90% of the year, indoor temperatures are between 20–26 °C, with regard to the thermal zone the building is located in, without applying the concept of adaptive comfort marked by the ASHRAE 55-2017 or by the EN 15251:2007 [17–19].

The use of adaptive comfort models, the analysis has been set out as one of the focal points for reducing energy consumption and lowering the emission levels of buildings. In this way, diverse thermal acceptability models of spaces have been generated around the world [18,19]. The objective of this article is to analyze the potential of using the adaptive comfort models of the ASHRAE 55-2017 and EN 15251:2007 standards versus those set out by the ECCS for housing. After that, the necessary improvements that need to be applied to current construction standards to maximize the time during which the building can work under free running conditions will be studied. This is justified by the fact that heating, ventilation and air conditioned (HVAC) equipment may be used only under extreme discomfort due to the users' limited resources [20]. In order to undertake an analysis of a dynamic simulation, a commonly used prototype of social housing with light construction systems was chosen as a case-study; it is located in the Bio-Bio region, lying in the Central–South fringe of Chile. This area features a Csb climate according to the Köppen–Geiger classification, where the average temperature during the hot season is below 22 °C and the average during the cold season is below 10 °C. These temperatures, though swinging between cold and hot, cannot be considered as extremes; therefore, the application of strategies related to thermal adaptation seems plausible. This is also supported by the fact that the current Chilean National Standards (ECCS) place the Bio-Bio region in thermal zone E, where the annual comfort percentage time must be 70%, with a lower limit of 20 °C and an upper of 25 °C [17]. In this way, a study focused on this region could be of interest, not only regarding the Chilean context, for evident reasons, but also for other audiences, because similar climates can be found in populated areas, such as the Mediterranean arch, the Northeast coastal area of the United States and Australia. Both the EU and the USA have already developed their own standards for adaptive comfort, and Chile is investing a great amount of resources in developing its own construction standards, such as the aforementioned ECCS, using the aforementioned countries as a reference.

By comparing and assessing the influence of a number of construction features in the applicability of such comfort standards, this research can make a contribution, targeting not only Chilean researchers but also stakeholders from other nationalities interested in the feasibility of a knowledge transfer between their countries and Chile. Selecting the best strategies will allow the provision of affordable comfort using a limited amount of energy, thus positioning Chile on the path of sustainable development.

In order to achieve this objective, this paper is divided into the following sections: First, Section 2 describes the materials and methods of the present research. The materials consist of an analysis of the different comfort standards and a description of the selected case-study, a prototype of social housing. The research methods consist of parametric simulations, performed using the software EnergyPlus®, on a combination of cases that will allow for better implementation of adaptive thermal comfort. Section 3 analyzes the results of the simulations, considering the application of the selected cases in terms of the thermal adaptive comfort models. Lastly, Section 4 delivers the main conclusions of this study.

2. Materials and Methods

2.1. Requirements and Policies for Social Housing in Chile

The Chilean State provided more than 3,671,646 subsidies to develop social housing between 1964 and 2015, investing around 19 billion euros in this policy since 1990 [21]. As such, substantial investment has been made to reduce the habitational shortfall to improve the quality of life for the most deprived sectors of Chile. At the present time, Supreme Decrees 01 and 49 are the legislative instruments that exist to provide subsidies to access to public housing [22,23]. Homes built privately or publicly under this financing can be arranged under a variety of typologies but should have a built surface area between 36.00 and 55.00 m^2. Figure 1 provides a model for the application of Supreme Decree 49, obtained from the online databank of Housing Projects. This is used by the Bio-Bio Region's Housing and Urbanization Service (SERVIU in Spanish) [24]. The geometry of these houses is quite standardized due to the surface area and budget limitations. Typically, they have two or three bedrooms, a living–dining area, kitchen and bathroom. Their construction features are associated with the local climate and availability of resources, being quite similar in the same region. In the case of the Bio-Bio region, they are built as single-family houses and they tend to feature light construction systems resting on a concrete base. The structural walls and roof structures are made from wood with different scantling; the outer side of the walls is constructed mainly with fiber cement siding, while inside, plasterboard is the common finish; the roof has corrugated zinc sheeting. The joinery is commonly done with aluminum or PVC with simple glazing, because their construction systems tend to have a high degree of airtightness and low thermal inertia [25].

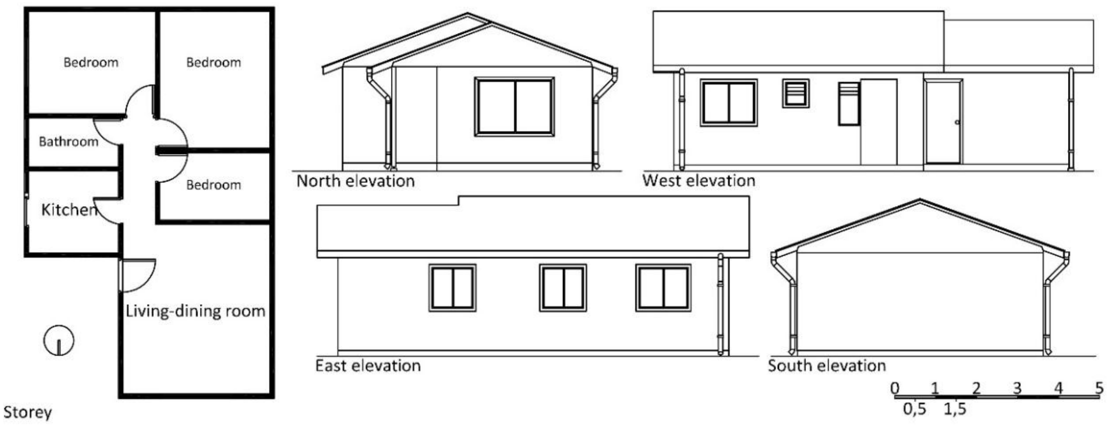

Figure 1. Housing model for the study.

Chile was the first country in Latin America to incorporate energy efficiency into their normative concepts, even though, historically, these demands had not been considered for buildings.

Currently, Art. 4.1.10. of the General Ordinance on Urbanism and Constructions (OGUC in Spanish) regulates the requirements that envelopes of homes associated with thermal transmittance must comply with. This article is mandatory, but its requirements are pretty limited [26]. The ECCS for Housing, whose requirements are more stringent, has also been produced, but, for the time being, it is optional [17]. Even so, it is necessary to point out that its standards are relatively limited when compared with other international standards (Table 1) [27].

Table 1. Limitations of transmittances, ventilation and airtightness for Concepción, OGUC (General Ordinance on Urbanism and Constructions) (title 4.1.10) and ECCS (Construction Standards with Sustainability Criteria) for Housing in the study region.

Case	U Gaps (W/m^2 K)			U Envelope (W/m^2 K)			Ventilation L/(s*person)	Airtightness (ACH50)
	<21%	21–60%	60–75%	Roof	Walls	Floor [(m^{2}K)/W]*100		
OGUC	>3.6	2.4–3.6	<2.4	0.38	1.7	150	-	-
ECCS		3.0 [1]		0.33	0.60	45	5.2	8

[1] The maximum glazing percentage is associated with the orientation: North <50%, South <40% and East–West <30%.

Because of this, Bustamante stated that even newly built buildings will be subject to future reconditioning due to the limited associated energy efficiency demands [20]. The same authors state that despite having a participation level of 21.3% in the country's energy consumption, most homes fall below the comfort temperature in winter due to the high fuel prices and low incomes, thus showing the importance of increasing the energy efficiency and inhabitability of already existent buildings or those being built. In addition, from an economic point of view, the low thermal performance level of homes in Chile costs the state around 0.8 billion € a year [28].

2.2. Adaptive Thermal Comfort Standards

In the search to create systems to assess the energy behavior of buildings, states have generated indicators associated with primary energy consumption—CO_2 emissions, or net energy supplied—creating global indicators which provide data related to the construction's energy efficiency [29]. The standards generally quantify the energy efficiency of the buildings based on the energy consumption or associated CO_2 emissions. This is evident, for example, in the EN 15603:2008, EN 15217:2007 standards as well as in the ECCS [17,29,30]. A classical approach for quantifying this consumption includes simulation of a fixed set point of temperatures, operating schedule or a combination of both. The ECCS has established that comfort temperatures for the coastal Southern area (Thermal area E) where Concepción, the largest city in the Bio-Bio Region, is located, must be between 20 and 25 °C. It is necessary to indicate that this temperature model is not the most suitable for assessing social housing as it does not tend to fit the real operating conditions of social housing. These tend to work under free oscillation except during extremely cold or hot situations.

The most extended adaptive comfort models, ASHRAE 55-2017 [31] and EN 15251:2007 [11,19] were established from the RP-884 and SCATs (smart control and thermal comfort, SCATs) research projects. These models are applied in buildings without active systems, where operable windows are easily accessed, and the occupants can adapt their clothing to the thermal conditions. Both models have established that an occupant's metabolic activity must be between 1.0 and 1.3 met (1.0 met = 58 W/m^2) and that it is possible for the clothing level to be between 0.5 and 1.0 clo (1.0 clo = 0.155 m^2 K/W).

In the case of ASHRAE 55-2017, two levels of thermal comfort are established based on the occupant's acceptability percentage. The first is associated with typical demand levels of 80% (1,2) and the second when a higher level of comfort is required (90%) (3,4), where θ_{rm} is the weighted running mean temperature.

$$\text{Upper limit of the 80\% acceptability comfort zone} = 0.31 * \theta_{rm} + 17.8 + 3.5 \quad (1)$$

$$\text{Lower limit of the 80\% acceptability comfort zone} = 0.31 * \theta_{rm} + 17.8 - 3.5 \quad (2)$$

$$\text{Upper limit of the 90\% acceptability comfort zone} = 0.31 * \theta_{rm} + 17.8 + 2.5 \quad (3)$$

$$\text{Lower limit of the 90\% acceptability comfort zone} = 0.31 * \theta_{rm} + 17.8 - 2.5 \quad (4)$$

In the case of EN 15251:2007, four types of inside comfort classifications have been established with regard to the expectations the occupants have, as well as other factors which are determined by the perception of comfort and the building's age (5,6,7,8). These are as follows:

- Category I: High level of expectation, recommended for spaces used by people who are weak and sensitive with special requirements, like the disabled, sick, very young children or the elderly (acceptability range—90%).
- Category II: Normal level of expectation, should be used for new or remodeled buildings (acceptability range—80%).
- Category III: Acceptable and moderate level of expectation, can be used for existing buildings (acceptability range—65%).
- Category IV: Values outside the criteria of the previous categories. This category should only be accepted during a limited part of the year (acceptability range <65%).

The following equations have been defined for Categories I and II which establish acceptable comfort limits (90% Category I and 80% Category II) and will be used to calculate the comfort zone limits of the housing under study:

$$\text{Upper limit of Category I comfort zone} = 0.33 * \theta_{rm} + 18.8 + 2 \quad (5)$$

$$\text{Lower limit of Category I comfort zone} = 0.33 * \theta_{rm} + 18.8 - 2 \quad (6)$$

$$\text{Upper limit of Category II comfort zone} = 0.33 * \theta_{rm} + 18.8 + 3 \quad (7)$$

$$\text{Lower limit of Category II comfort zone} = 0.33 * \theta_{rm} + 18.8 - 3 \quad (8)$$

$$\theta_{rm} = (\theta_{ed-1} + 0.8 * \theta_{ed-2} + 0.6 * \theta_{ed-3} + 0.5 * \theta_{ed-4} + 0.4 * \theta_{ed-5} + 0.3 * \theta_{ed-6} + 0.2 * \theta_{ed-7})/0.8 \quad (9)$$

In both methods, for the calculation of the average operating temperature (θ) of a concrete day, the outside average temperatures of the seven previous days are used, with θ_{ed-1} being the average daily outside temperature of the previous day; θ_{ed-2} is the average outside temperature of the day before that and so on and so forth using Equation (9). These average daily temperatures throughout the 365 days of the year are compared with the operating temperatures of the 8760th h of the year and are evaluated within the 80% and 90% limits of both ASHRAE 55-2017 and Category I and II of EN 15251:2007.

The adaptive comfort models have a use limitation related to the average outside operating temperature. When the temperature falls below 15 °C for EN or 10 °C for ASHRAE, a minimum comfort temperature is established. For EN 15251, the minimum thermal comfort temperatures are 20 °C for Category II and 21 °C for Category I, and for ASHRAE 55-2017, these are 18.4 °C for the 90% thermal acceptability and 17.4 °C for 80% thermal acceptability. This means that the equations used to calculate the adaptive comfort temperatures cannot be used during the entire year in moderately cold climates like that of Concepción.

2.3. Methodology

The current research's methodology is focused on evaluating the percentage of time during which social housing falls within comfort ranges based on the different demands. For this, the results obtained through the ECCS comfort levels and the adaptive comfort models of ASHRAE 55-2017 and EN 15251:2007 were compared. After evaluating the differences between the application of the different models, a battery of strategies was used with the goal of improving the base case. The goal of this second study is to analyze which one of the implemented improvements is more effective when it comes to extending the free-running time, thus determining the potential of using adaptive comfort models versus the static models.

The battery of strategies was simulated parametrically in EnergyPlus® simulation software [32] using the prototype of social housing depicted in Figure 1, located in the city of Concepción (Chile). The case was chosen from the Project Bank of the Bio-Bio Region's Housing and Urbanization Service (SERVIU) due to being the most representative among the typologies used [24]. Priority was given to the choice from this document, due to these all being detached houses and having a higher surface area of the envelope exposed, as this assumes, a priori, more unfavorable thermal behavior in this climate [33].

Parametric simulations were carried out using the housing prototype depicted in Figure 1. Table 2 represents constructive standards for this prototype, which are grouped into transmittances, ventilation, infiltration and special solutions. At first, a base case was compiled with the following considerations: Transmittance (U values) were adjusted to the minimum values per ECCS, which is still not mandatory but much more restrictive than the already enforced Art. 4.1.10 of the OGUC. Ventilation rates were adjusted on a 24 h basis, in accordance with the minimum recommended values per the ECCS, while infiltration rates were adjusted also as per the minimum values required by the ECCS.

In this way, taking case 1 as the base case, several improvements in these four areas have been implemented and simulated. The first group of improvements consisted of elevating U values (cases 2–5); the second group consisted of adjusting ventilation rates depending on the season of the year (cases 6–8); the third group consisted of implementing an ON-OFF ventilation scheme over a 24 h period, which is described in Figure 2 (case 9); the fourth group reduced infiltration to 0.35 ACh (case 10); the fifth group implemented two special solutions for the building skin: a high absorbance material and a high thermal mass (cases 11–12). These first 12 cases are defined as "simple parametrization cases". After analyzing the results from these 12 different possibilities, those ones with the best results were selected and therefore combined into four additional parametric cases, denoted as "complex parametric cases". Case 13 combines the results from case 8 plus case 10; case 14 combines cases 5, 9 and 10; case 15 combines cases 5, 9, 10 and 11; and lastly, case 16 combines case 9 plus case 10. Finally, the results were analyzed to prioritize the implementation of enhanced construction standards in terms of the percentage of time during which the house can be in a free-running state.

Table 2. The model's parametrization data.

Case	U Openings (W/m² K)	U Envelope (W/m² K)			Ventilation L/(s*person) [1]				Infiltration (ACh)	Special Solutions
		Roof	Walls	Floor [(m²K)/W]*100	Time	Months 5,6,7,8	Months 4,9,10	Months 1,2,3,11,12		
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	0.2	0.35	0.3	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	T. absorptance 0.9
12	3.16	0.33	0.50	45	24 h	5.2	5.2	5.2	1	∆ thermal mass
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	∆ thermal mass
16	3.16	0.33	0.50	45	ON-OFF	2.0	3.5	10	0.35	-

[1] Months in which each ventilation flow is applied.

Regarding the ventilation rates, additional comments should be made. In mild climates such as the one found in the Bio-Bio region, natural ventilation plays a crucial role in thermal comfort [34], in accordance with adaptive thermal comfort standards, such as ASRAE 55-2017 and EN 15251. Therefore, the base case for natural ventilation has been set as 5.2 L/s per person, per ECCS, during all times of the year. After that, this scheme has been tuned step-by-step using different possibilities in order to maximize the potential of ventilation as a method for achieving comfort. Primarily, the ventilation rate has been adapted on a yearly basis, according to a classification that includes very cold (May, June, July and August), cold (April, September and October) and warmer months (January, February, March, November and December). After that, the former rate has been further adjusted on a 24 h basis. In addition, internal loads have been considered in all of the models. Occupation, lighting, equipment and ventilation loads (Table 3) as well as schedules (Figure 2) have been obtained from the ECCS (Figure 3).

Table 3. 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

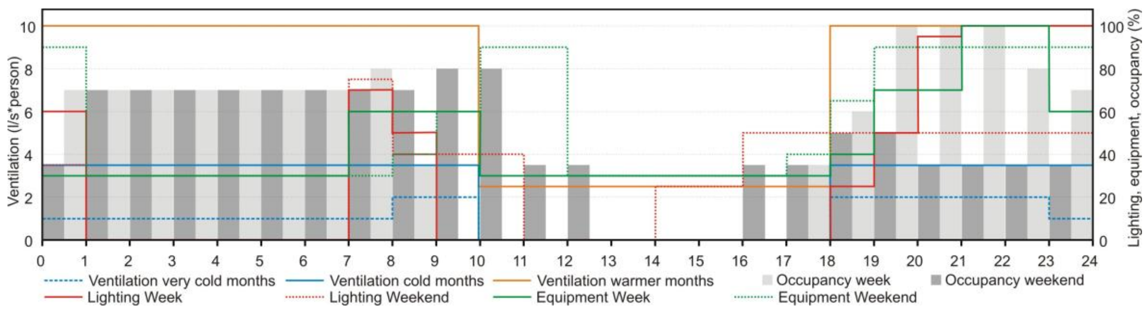

Figure 2. Occupation, lighting and equipment and ventilation schedules.

3. Results

3.1. Analysis of Comfort in Social Housing Following the Evaluation Model Used

The adaptive comfort models establish different temperature ranges depending on the outdoor temperature. According to the evaluation proposed by ASHRAE 55-2017 and EN 15251:2007, it is considered that the building is within comfort limits if the following criteria is met: First, in the 90% range (Category I for EN) occupants may be slightly mild or cold; this range is reduced in the 80% range (Category II for EN) [18,19]. Therefore, if criteria for category II are met, the building can be catalogued as "comfortable" without the use of active conditioning systems.

The housing model under free oscillation has been simulated to compare the comfort standards established for the ECCS with adaptive models, evaluating indoor temperatures by different thermal well-being criteria (Figures 3 and 4). It is necessary to indicate that the comfort model defined by ECCS, which we could call "static", has a less extensive temperature range than the adaptive models, being 5 °C, independent of the conditions [17]. ASHRAE's adaptive model has a daily range of 7 °C for 80% acceptability and 5 °C for 90%. The EN has a daily range of 6 °C as a maximum for Category II and 4 °C for Category I. However, their limits are not constant and adapt depending on the outdoor temperatures, as can be seen in Figures 3 and 4. This means that adaptive standards are closer to the thermal behavior of social housing under the free oscillation system [7].

The buildings located in the city of Concepción mainly have problems associated with low temperatures (Figures 3 and 4), reaching indoor temperatures close to 10 °C during the winter months. Overheating issues can be seen during the hottest months, but these are minimal compared with those of the colder temperatures. For this reason, the improvement measures have mainly been focused on the colder period, although summer measures were included (Table 2).

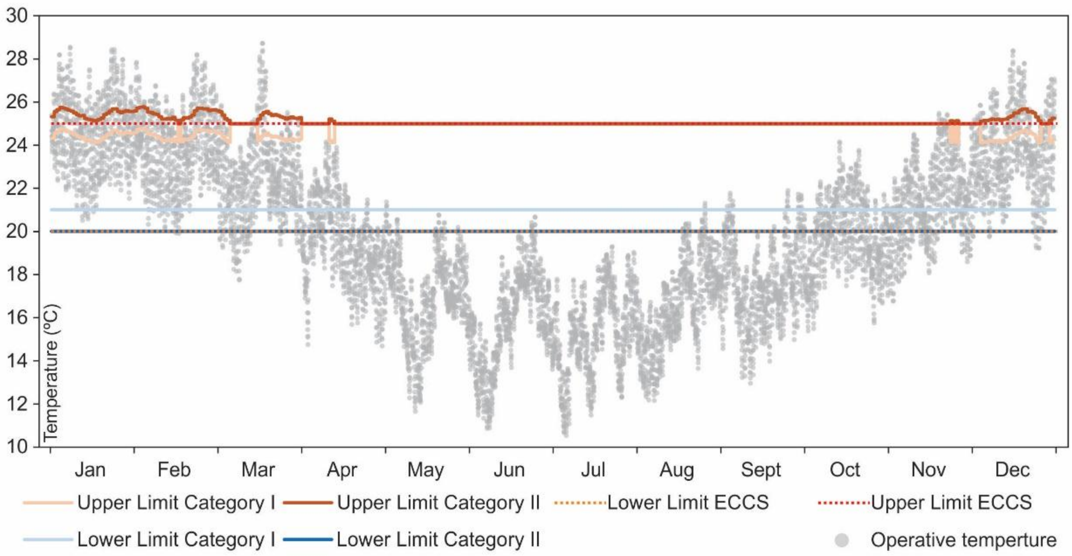

Figure 3. Operative temperature of the housing (case 1) using the limits established by ECCS and by EN 15251:2007.

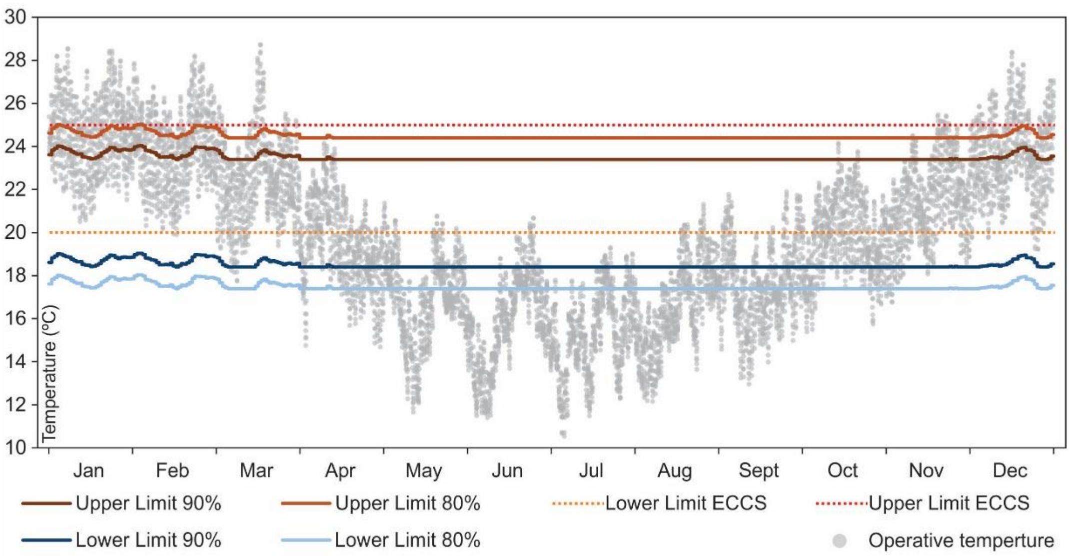

Figure 4. Operative temperature of the housing (case 1) using the limits established by ECCS and by ASHRAE 55-2017.

It can be seen in Figures 3 and 4 that the static comfort model (ECCS), with its a smaller temperature range, has worse results than the adaptive models. According to ECCS, the building is within adequate temperature ranges 39% of the time. However, when applying EN's adaptive system, this percentage is 41.23% (Figure 3), considering that the temperatures within the ranges of Types I and II are suitable for avoiding artificial condition systems. According to ASHRAE (Figure 4), thermal comfort is achieved 59.66% of the time, using the 80% limits. With regard to the thermal discomfort conditions, it is necessary to indicate that the EN 15251:2007 standard, using Category II, does not reduce the time during which cold conditions are observed, if compared with ECCS (52.31%). However, regarding ASHRAE, this time is reduced by 22.82%. All three models indicated short periods of time associated with high temperatures: 8.70% for ECCS, 6.46% for EN and 10.86% for ASHRAE.

The ECCS for housing indicates that a building can dispense with air-conditioning systems if it falls within comfort ranges at least during 70% of the time, establishing, in this way, the aforementioned temperatures [17]. On comparing the results, it is seen that to reach this percentage, it would be necessary to increase the comfort conditions by 31% in the case of ECCS, 28.77% for EN 15251:2007 and 10.34% for ASHRAE 55-2017. Because of this, the simple application of ASHRAE's adaptive thermal comfort model has relevant potential: a dwelling can work under free oscillation during an important part of the year. This would also occur if Category III of the EN norm is applied. However, it has been decided to use Category II so that the thermal acceptability percentage is similar between both adaptive standards.

3.2. Analysis of the Improvement of the Standards for Low Energy Consumption Housing

The ECCS establishes some basic standards for the building of homes, defining the transmittance, thermal mass, internal loads, ventilation, infiltration and use profile requirements for the climate zone of Concepción (Zone E). A first analysis of an ECCS based model (Case 1) was done to improve current standards, identifying the associated indoor comfort problems of the model and proposing 11 improvements to the base model and four combinations with the basic cases that would offer the best results.

Cases 2, 3, 4 and 5 are associated with improvements to the envelope's thermal transmittances; cases 6, 7, 8 and 9 are associated with the housing's natural ventilation flow; case 10 is associated with infiltration; and cases 11 and 12 are associated with special improvements related with to the absorptance of the roof and the increase in the housing's thermal mass. It has been considered suitable to analyze results using the static comfort model and to compare these with the adaptive models that offer a higher use potential of the housing's indoor temperatures under free oscillation and a closer match to the housing's real operation.

Improvements 2 and 3 consisted of reducing the wall opening's transmittances, including PVC joinery and glazing with an 6/12/6 air chamber, with model 3 having low emission. The results indicated that considerably improving the glazed surfaces under 3.16 W/m^2 K does not increase the home's comfort time. In fact, it even reduces it when applying the standards of the ECCS and the European Norm (EN 15251:2007) −0.03% and −0.10%, respectively; however, for the American standard (ASHRAE 55-2017), the comfort times are increased by 0.89% and 1.27%, respectively. Due to the limited impact of these improvements on the building, these have not been considered for the cases with combined measures (Table 2). Likewise, the reduction of the thermal transmittances of the opaque enclosures does not mean an important increase in the housing's comfort, increasing it by 1.87% and 1.44% for EN; 1.34% and 0.11% for ECCS, and 1.60% and −0.24% for ASHRAE. Unlike what would occur with the improvements in glazed surfaces, the low impact of the reduction of transmittances means is associated with a reduction in the percentage of time with low temperatures (5.35% and 8.45% ASHRAE; 4.47% and 7.68% ECCS; 4.47% and 7.68% EN) and a similar increase in the time that the housing would be over the thermal comfort limits (3.76% and 8.69% ASHRAE; 3.14% and 7.57% ECCS; 2.60% and 6.24% EN) (Table 4). Therefore, despite the fact that this improvement does not lead to an increase in the comfort conditions, it has been considered appropriate to include it, given that the high temperatures can be adjusted via free-cooling with natural ventilation.

Following the analysis of the results of the base case (Figures 3 and 4), it was seen to be appropriate to establish better standards for the housing's operation during summer and winter. In the base case, the time percentage where the thermal comfort limits were exceeded due to overheating was relatively small, compared to the problems associated with low temperatures, despite these representing 10.86% for ASHRAE, 8.70% for ECCS and 6.46% for EN. Because of this, the months and hours of the years in which the indoor operating temperatures are higher than the comfort temperatures have been analyzed, and it has been determined that the natural ventilation must be increased to 10 L/(s*person) during November, December, January, February and March and reduced in the coldest months (May, June, July and August).

In models 6 and 7, the natural ventilation flows are adjusted for the months of November, December, January, February and March, from 5.2 L/(s*person) to 10 L/(s*person) and in case 7 the ventilation flow of the coldest months is reduced from 5.2 L/(s*person) to 3.5 L/(s*person). As can be seen in Table 4, the adjustment of natural ventilation rates during hot periods increases the comfort time by 11.10% for ASHRAE, 3.54% for ECCS and 2.41% for EN. The flow reduction in the coldest months also considerably increases the housing's thermal comfort hours, by 3.76% for EN 4.85% for ECCS and 12.20% for the American standard. Because of this, this measure forms part of the four combined models, i.e., a ventilation rate for these models of 2.0 L/(s*person) for the very cold months, 3.5 for the colder months and 10.0 for the hot months.

Table 4. Percentage of time in different environmental situations using the comfort model.

Case	Cold (%)	Slightly Cool (%)	Comfort (%)	Slightly Warm (%)	Hot (%)	Total Comfort (%)	Difference
ECCS (Zone E)							
1	52.31		39.00		8.70	39.00	
2	54.30		38.96		6.74	38.96	−0.03
3	54.22		39.11		6.67	39.11	0.11
4	47.83		40.33		11.84	40.33	1.34
5	44.62		39.11		16.27	39.11	0.11
6	54.25		42.53		3.22	42.53	3.54
7	52.77		43.85		3.38	43.85	4.85
8	51.47		45.15		3.38	45.15	6.15
9	47.29		47.79		4.92	47.79	8.79
10	44.66		39.92		15.42	39.92	0.92
11	50.66		38.26		11.07	38.26	−0.73
12	55.17		42.75		2.08	42.75	3.76
13	39.04		55.24		5.72	55.24	16.24
14	10.35		70.40		19.25	70.40	31.40
15	20.10		70.23		9.67	70.23	31.23
16	35.07		56.68		8.25	56.68	17.68
EN 15251:2007							
1	52.31	7.75	28.29	5.19	6.46	41.23	
2	54.30	7.95	28.12	5.07	4.57	41.13	−0.10
3	54.22	8.05	28.28	4.94	4.51	41.27	0.03
4	47.83	7.90	28.61	6.60	9.06	43.11	1.87
5	44.62	8.04	26.61	8.03	12.71	42.67	1.44
6	54.25	11.66	29.03	2.96	2.11	43.64	2.41
7	52.77	12.01	29.91	3.07	2.24	44.99	3.76
8	51.47	12.49	30.73	3.07	2.24	46.29	5.06
9	47.29	12.44	32.60	4.41	3.25	49.45	8.22
10	44.66	7.83	28.57	6.13	12.81	42.53	1.30
11	50.66	7.50	27.90	4.94	9.00	40.34	−0.89
12	55.17	7.00	32.69	4.81	0.33	44.50	3.26
13	39.04	14.16	38.37	4.37	4.06	56.89	15.66
14	10.35	10.35	55.42	7.73	16.14	73.50	32.27
15	20.10	15.27	49.25	10.26	5.11	74.78	33.55
16	35.07	13.90	39.81	5.05	6.18	58.76	17.52
ASHRAE 55-2017							
1	29.49	9.83	42.69	7.13	10.86	59.66	
2	30.86	9.90	43.56	7.09	8.60	60.55	0.89
3	30.66	9.90	43.82	7.20	8.41	60.92	1.27
4	24.13	9.87	42.59	8.79	14.61	61.26	1.60
5	21.04	9.32	40.83	9.27	19.54	59.42	−0.24
6	25.02	11.42	53.24	6.10	4.22	70.75	11.10
7	23.74	11.21	54.29	6.36	4.39	71.86	12.20
8	20.53	10.54	58.18	6.36	4.39	75.08	15.42
9	16.75	10.24	59.25	7.16	6.61	76.64	16.99
10	21.47	9.00	42.71	8.70	18.13	60.40	0.74
11	28.09	10.01	41.21	7.28	13.40	58.50	−1.15
12	35.75	7.92	43.29	9.85	3.18	61.06	1.40
13	10.90	8.95	64.21	8.23	7.71	81.39	21.74
14	0.47	1.88	55.66	16.87	25.11	74.42	14.76
15	0.00	0.90	70.10	16.07	12.92	87.08	27.42
16	8.70	7.74	63.66	8.66	11.23	80.07	20.41

In case 9, three operation schedules have been incorporated, depending on the month. The occupation of the housing and its use have been considered in the schedule (See Figure 2). The main flow regulation schedule is produced between 18:00 and 10:00, as residential buildings are mainly used during this time, being also the period when heating issues occur. This improvement produces an 8.22% increase in the housing's comfort time according to EN and 16.99% for ASHRAE, indicating that this is an acceptable measure for reducing the building's indoor temperatures when being assessed with both standards. Therefore, it was decided it would form part of cases 14, 15 and 16.

With regard to air infiltration, it is necessary to indicate that the ECCS establishes an air leak class of 1 ACH, considering the improvement associated to the lower temperature which, for case 10, is reduced to 0.35 ACH. In this case, according to EN, the indoor conditions are improved 1.30% of the time, increasing the discomfort due to heat situations by 6.35% and reducing the temperatures under the comfort limits by 7.65%. In case 10, according to ASHRAE, the improvement is produced 0.74% of the time, with the heat situation increasing by 7.27% and cold decreasing by 8.01%. Just as occurred with the reduction of the thermal transmittances, it has been considered appropriate to include this in the combined measures, as the high temperatures can be adjusted using free-cooling with natural ventilation.

Models 11 and 12 consider passive measures associated with the envelope's thermal behavior, the first associated with improving the gains through the roof's radiation to improve indoor conditions associated with the cold, and the second, with the increase in the housing's thermal mass to increase its storage and thermal damping capacity. The application of improvement 11 does not assume an increase in the comfort conditions as can be seen in Table 4 (EN −0.89%, ECCS −0.73% and ASHRAE −1.15%).

Model 12 would have a negative impact of 3.26% for EN, while for the American standard, it would mean a comfort increase of 1.40%, partially reducing the problems associated with overheating. For ECCS, the thermal mass increase would mean reducing the overheating by 6.62%. It is necessary to indicate that the ECCS establishes that, for the thermal zone where the case study is located, the housing must have a light thermal mass 0–70 (kJ/m^{2}K), but the results show that it is suitable to increase the calorific capacity by between 200–400 (kJ/m^{2}K) to avoid overheating problems. Therefore, this solution has been implemented within one of the combined cases.

Model 13 has considered all the natural ventilation improvements which means an increase in comfort and reduction of infiltration; it produces a natural ventilation rate of 2.0 L/(s*person) during the coldest months, 3.5 L/(s*person) during cold months and 10.0 L/(s*person) during the warm months, including a leak rate of 0.35 ACH. For model 16, the ventilation operation schedule evaluated in case 9 has been incorporated. Model 13, according to EN and ASHRAE improves the comfort conditions by 15.66% and 21.74%, respectively, and model 16 by 17.52% (EN) and 20.41% (ASHRAE). Thus, it is seen that, according to the European Model, it is essential that the housing's natural ventilation flows is regulated in accordance with the outdoor conditions; however, for the American model, this would mean practically no benefit whatsoever.

Model 14 has been formed by the combination of the measures of models 5, 9, 10, thus regulating the ventilation and the infiltration and reducing the thermal transmittance of the envelope's opaque enclosures. The grouping of the measures offers a satisfactory result as it increases the housing's comfort time by 32.27% using EN, 31.40% using ECCS and 14.76% according to ASHRAE; therefore, the combination of these improvements means a very important comfort increase for EN and ECCS; however, for ASHRAE there is not such an important increase in the comfort conditions (Table 4).

The combination of these measures with the thermal mass increase (Model 15) means that the building's behavior increases considerably with this model 74.78% of the time, being within the comfort values established by EN 15251:2007 for Category II which would mean an increase of 33.55% versus case 1. With regard to ASHRAE, this model is within the comfort values 87.08% of the time, applying the ranges for 80% of thermal acceptability, which would mean an increase of 27.42% versus case 1. In the case of ECCS, this would mean an increase of 31.23% with a total percentage within the 70.23% limits.

On analyzing Figure 5, the housing's indoor operative temperatures versus the average outdoor operative temperature are seen, calculated based on the EN 15251:2007 and ASHRAE 55-2017 norms. It can be seen that only 2209 h are outside the Category II limits and 1132 h out of the 8760 h of the year are outside ASHRAE's 80% limits. In the American norm's case, this is always due to heat. However, on applying ECCS's temperature range, that figure would be increased to 2608 h, of which 1761 h would be due to the cold. It is necessary to indicate that if Category III of the EN 15251:2007 norm had been applied, case 15 would have almost 100% of the time in comfortable conditions, with 7 h under the comfort limits and 22 h over the limits.

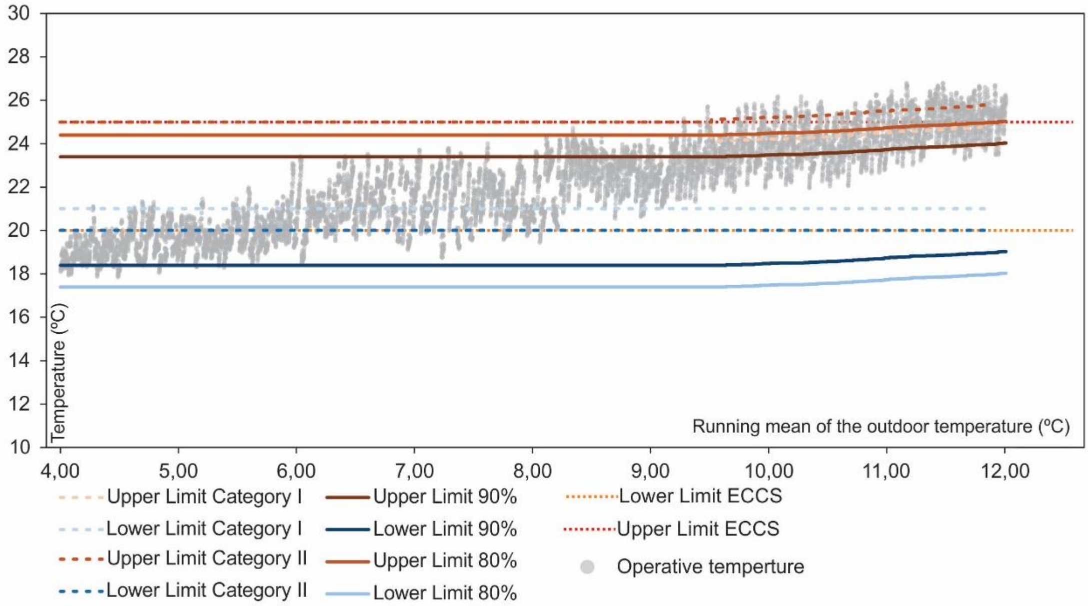

Figure 5. Spread of operative temperatures and mean outdoor temperatures of case 15 versus the limits set by ECCS, by EN 15251:2007 and by ASHRAE 55.

This indicates that the adaptive comfort models have a lot of potential to evaluate the potential of a building to operate under free oscillation without considering active energy consumption measures but, at the same time, very different results can be obtained depending on the model chosen for the evaluation.

Therefore, to have housing that can be naturally ventilated in Concepción, it is necessary to increase the requirements associated with the transmittances, ventilation, infiltration and thermal mass, with the housing being able to operate for 70% of the year without an air-conditioning system, even reaching 100% if Category III of the EN 15251:2007 norm is applied.

4. Conclusions

This research focused on clarifying which construction strategies have a greater influence on the thermal comfort of inhabitants, considering a social housing prototype located in the region of the Bio-Bio and analyzed under two international standards (EN 15251:2007 and ASHRAE 55-2017 adaptive comfort models) and one national standard (Chilean ECCS). Looking at the results, the following conclusions can be drawn.

Results for the three standards analyzed are coherent. The base case (case 1) was always amongst the worst options regarding comfort; the complex cases (13–16) offered the best results and the in-between cases (2–12) offered similar patterns of improvement. This tells that results in numerical terms can be different depending on the standard, but all of them will point in the same direction, so that the three of them can find application in this context and the improvements will also have a similar effect even when considering different criteria.

Going deeper, it can be highlighted that the ASHRAE standard is the least flexible, so to speak, when different constructive improvements are applied to increase the period of time in thermal comfort. On the other hand, the Chilean ECCS shows greater dependence on the application of such improvements; the European standard is in between both of them. It is remarkable how a standard with such fixed comfort threshold temperatures (ECCS) is in need of constructive improvements, whereas those with adaptive limits are not. In other words, adaptive thermal comfort implies a non-dependence on constant upgrading of constructive systems.

The analysis has clarified that, under the three standards, a social dwelling prototype located in the region of the Bio-Bio will reach it best operation under three complex cases (cases 14–16). Regarding construction, this would mean having low U values for the roof, walls and floors, but not necessarily for openings. The most important feature, present in the three of them, is having an adapted ventilation scheme on a yearly and a 24 h basis, and reduced airtightness; additionally, thermal mass could be an asset, but its effect would not be so notable, except for when the ASHRAE standard is used. These conclusions pose an interesting debate about the real effectiveness of a constant increase in U standards in mild climates. In this case, it has been proven that, despite high U values being beneficial, an improved ventilation scheme is much more effective when trying to reduce dependence on HVAC systems.

It is possible to reach 80%, or nearly 80%, of time in thermal comfort in this climate under certain situations. The remaining time, discomfort is associated primarily with a cold environment, rather than with hot weather; at this point, it has been proven that heating systems would play a significant role for 20–30% of the year, but always in combination with a carefully designed ventilation scheme and improved airtightness.

The results of this research are oriented towards the tight relationship between building construction and building operation, focusing on social dwellings, whose inhabitants operate in close relation to adaptive comfort. The results can be beneficial, for public policies that aim to decrease the energy consumption of buildings. Not only better constructive standards, but also intelligent and adapted patterns of use, are of capital importance when trying to reach this objective. International standards can find application in different national contexts, always having in mind the particularities, necessities and level of development of each socioeconomic reality.

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