Determination of Optimal Thermal Inertia of Building Materials for Housing in Different Chilean Climatic Zones

Constanza Avendaño-Vera[a], Aner Martinez-Soto[a,*], Valentina Marincioni[b]

[a]Department of Civil Engineering, Faculty of Engineering and Science, Universidad de La Frontera, Temuco, Chile
[b]UCL Institute for Environmental Design and Engineering, University College London, London, UK

***Corresponding Author:** Aner Martinez Soto
Department of Civil Engineering, Universidad de La Frontera
Temuco, Francisco Salazar, 01145 Temuco, Chile
Tel 00 56 45 2596816
Email aner.martinez@ufrontera.cl

ABSTRACT

In recent years, several studies on residential energy consumption and new strategies to reduce it have been carried out. The literature reports that although thermal inertia can influence energy demand, it is associated to greater extent with the thermal comfort of the buildings. The performance of thermal inertia in buildings located in different regions or countries has been analyzed, comparing high and low thermal inertia structures or materials through energy simulations or empirical studies. However, the optimal thermal inertia of a building according to different climates has not been established. In this study, optimum values are determined for the different properties that define thermal inertia (thermal conductivity, specific heat capacity, and density) that would allow to maintain the indoor annual operative temperature within the thermal comfort range (18-24°C) of a standard dwelling. Energy simulations were carried out in DesignBuilder using climate data from 10 cities in different Chilean climatic zones. The results show the minimum thermal conductivity as optimal regardless of climate (0.025 and 0.03 W/m K), while the optimal density ranges fluctuate between 1800 and 2500 kg/m^3 varying according to their climatic classification. Finally, it was determined that specific heat capacity was not influential in the thermal comfort of the analysed dwelling.

Highlights

- Low thermal conductivity and high density determine an optimal thermal inertia.
- There are no existing materials that meet the optimal values of thermal inertia.
- Wood and lightweight concrete are the closest materials to the optimal material.
- Materials with optimal thermal inertia improve thermal performance of buildings

Keywords: thermal inertia; thermal comfort; optimization; climate zone; energy efficiency; building envelope.

Word count: 9172

Nomenclature

ANOVA	Analysis of Variance
MINVU	Ministry of Housing and Urban Development
OGUC	General Ordinance on Urban Planning and Construction
OECD	Organization for Economic Co-operation and Development
TOTCR	Temperature degrees outside the thermal comfort range [Ka]
ADP	Atmospheric Decontamination Plans
NCh	Chilean regulations
MP	particled matter
CDD	The Cooling Degree Days
HDD	Heating Degree Days
$S_{i,j}$	sensitivity coefficient
TI	Thermal inertia
λ	Thermal conductivity [w/mK]
C_p	Specific heat capacity [J/kgK]

ρ	Density [kg/m^3]
BWm	Desert with abundant clouds
BWk'	Cold Desert
BWk	Normal Desert
Csbn	Warm temperate with winter rains and high cloud cover
Csb	Warm temperate with winter rains
Cfsb	Rainy with Mediterranean influence
Cfc	Temperate cold rainy without dry season
BW	Desert climate
Cs	Warm temperate climate
Cfs	Rainy climate
U	Thermal transmittance [W/m^2 K]
Umax	Maximum thermal transmittance [W/m^2 K]
Ug	Thermal transmittance of windows
T_b	Base temperature [°C]
To_i	Operative temperature [°C]

1.0 INTRODUCTION

Energy used in residential and commercial buildings accounts for 20.1% of the total energy consumed globally and increases on average by 1.5% per year in OECD countries [1]. In recent years, a number of studies have been carried out on residential energy consumption [2][3][4][5][6] and it has been determined that it is sensitive to temperature variations [2], the duration of the annual heating period [7] and thermal insulation [7]. Additionally, recent studies show that thermal inertia (defined as the responsiveness of a material to temperature variations [8]) can influence the energy demand of dwellings [5][6][9] and have a positive impact on the thermal comfort of users [10].

It has been shown that in buildings with high thermal inertia (TI) there are fewer temperature fluctuations [11], which, in some cases, could result in a reduction in energy for both heating and cooling [9]. However, obtaining positive effects from a high thermal mass depends on a number of factors, such as climatic conditions and acceptable indoor temperature requirements [11].

The results of energy simulations from previous studies that considered daily outdoor temperature oscillations between 0 and 10°C show that passive energy storage through high thermal mass can change energy consumption and be beneficial [11]. However, the positive effect of TI is most noticeable for warm or Mediterranean climates [12] and for warmer and drier seasons [13]. Additionally, different impacts of the use of construction layers with TI are observed in studies carried out in very different climates. In arid regions, such as Saudi Arabia, it has been concluded that increasing and optimizing thermal mass can reduce energy demand in the autumn and spring months, generating annual savings of 17% in cooling and 35% in heating [6]. In Norway, on the other hand, where this is a subarctic climate, the use of heavy thermal mass combined with ventilation provides a small reduction in the energy used for heating, but a reduction of up to 12% for cooling [5].

Research in Italy has also shown that the proper interaction between thermal mass and ventilation reduces overheating and excessive cooling in dwellings [14]. However, it was determined that if the internal gains and solar gains were controlled, favourable energy yields could be achieved in the summer period [15].

There are empirical studies [13][16][17] conducted in Italy that compared the thermal performance of construction solutions with high and low TI. It has been shown that using a wall with high internal TI can reduce the hours of thermal discomfort in summer by between 6% and 14% [16]. Yet, it has been proven that the use of basalt stone walls in buildings in southern Italy represents a better solution than the use of double bricks, as they attenuate temperature fluctuations, improving thermal comfort by avoiding excessive overheating [17].

Recently, phase change materials (PCM) have been used as a way to increase the TI of a building [10], which has contributed to a decrease in energy consumption [18] [19]. For example, using PCM allowed a 15% reduction in the total energy consumption of a building located in Toronto [18] and 18% in another study conducted at Diyarbakır, Turkey [20]. Another study states that using PCM allows energy savings through the availability of natural cooling [21]. However, the magnitude of the benefits obtained are different depending on the season [22] and the geographical location [20]. Additionally, it is pointed out that the appropriate choice of PCM will depend on the climatic conditions of each case [18][19].

Although there is consensus on the effects and benefits of using constructive solutions with high thermal masses, it is inferred that the results and effects are highly dependent on climate and may therefore differ between them. Additionally, it is observed that in previous studies, climates are referred to as *warm* or *cold*. As both terminologies do not refer to a standardised climate classification, the interpretation of the results can be subjective and the transferability of conclusions in areas with similar climatic conditions is hampered.

The empirical comparison of construction systems gives indications of the real effects of the use of materials with high TI. However, it does not allow us to conclude exactly which is the optimal TI for each case studied. In addition, as this approach is limited to using values from existing materials, it makes it difficult to obtain values other than those already known and thus to develop new materials with new thermal characteristics.

The aim of this study is to quantify the influence of the different properties that define TI (thermal conductivity, specific heat capacity and density) on achieving comfortable indoor temperatures in a typical dwelling; the optimization was based on minimizing the number of degrees outside the thermal comfort range (18-24 °C). Chile was considered as a case study for the analysis, since it allows determining the effect of TI in very different climates with their equivalents in the international classification of Köppen (example: desert, semi-desert, rainy, coastal or Mediterranean climates). Thus, the optimal TI figures determined in this study can be reused in localities with similar climatic conditions. In this sense this study aims to contribute to the formation of theoretical foundations for the development of new materials or future research on the energy efficiency of housing based on the combination of insulation and TI.

2.0 METHOD FOR THE DETERMINATION OF THE OPTIMAL THERMAL INERTIA FOR HOUSES IN DIFFERENT CHILEAN CLIMATIC ZONES.

The objective of this study was to determine the optimal TI properties that result in annual indoor operative temperatures within the thermal comfort[1] range, defined in this case as the temperature between 18 and 24°C [23]. The optimal building material was considered to be one that had a combination of properties that recorded a lower annual sum of degrees outside the thermal comfort range (18-24°C) represented in Figure 5.

The optimal value can also be defined in terms of the energy expenditure of a dwelling, since it has been stated that TI in turn has an influence on energy demand [6][9][10][11]. However, energy consumption in the residential sector depends on factors such as energy prices, characteristics of buildings or dwellings, efficiency and type of equipment, and access to or availability of energy sources and energy policies [1]. For this reason, the analysis in this study was carried out with respect to thermal comfort temperature and only the influence of

---

[1] Thermal comfort is defined as the users' thermal satisfaction with the surrounding environment and is mainly influenced by factors such as temperature, humidity and air speed [24].

the variables of the TI and climatic zone variables would be considered in order to facilitate the transferability of the results of this work.

The methodology used in this study was based on energy simulations carried out on a typical house located in different climatic zones of Chile. For this purpose, climatic data from cities belonging to different climatic zones of the country were used and a typical house was designed according to the current thermal conditioning regulations and the statistical studies carried out on housing in Chile. In this sense, it should be clarified that this study has a theoretical approach and that the results obtained do not imply the existence of a material with such optimal properties.

2.1 Determination of Climatic Zones for Modelling

For the classification of the Chilean territory in the climatic zones considered in this study, the current regulations were revised that propose the subdivision of the country into zones with similar thermal characteristics (degrees days) and climatic characteristics (temperature, solar radiation, humidity, rainfall, among others). It was determined that for this study the most appropriate subdivision of zones is the one proposed in the Chilean regulation 1079 "Architecture and Construction - Housing Climate Zoning for Chile" (NCh 1079) [25], since it establishes a housing climate zoning based on the antecedents provided mainly by the Meteorological Direction of Chile and unlike the other regulations, this one considers all the relevant a climate parameters.

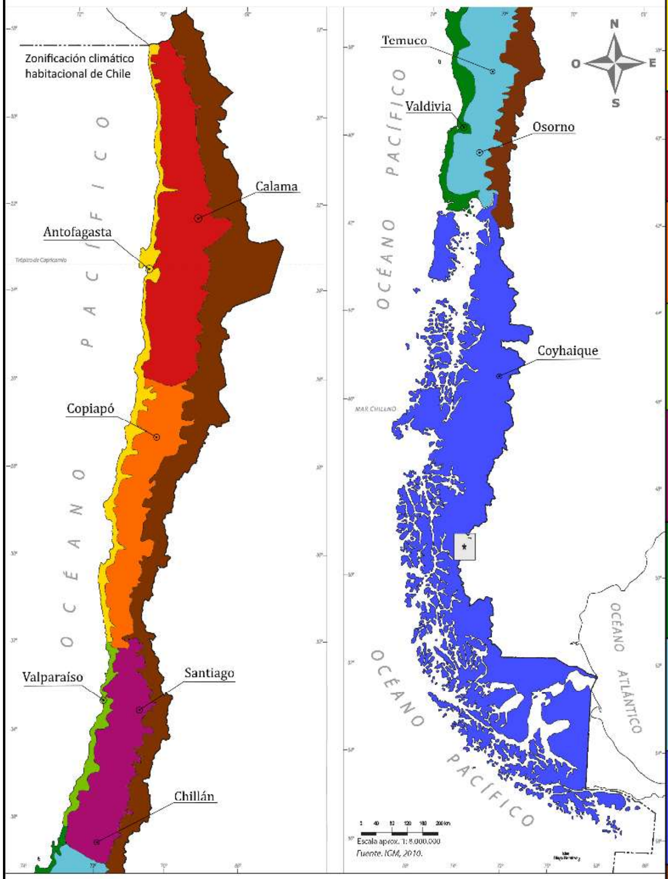
The climate zones established in NCh 1079 cover large areas of territory, but the climate data available for simulations in the DesignBuilder software are linked to specific cities. For this reason, cities located in each climate zone were selected in order to use their climatic background. The criterion for selecting these cities was to be a regional capital or city with a greater number of dwellings in order to improve the representativeness of this study. Of the nine climatic zones mentioned in the regulations (NCh 1079), the Andean zone was not part of the study, because it was not possible to obtain a climatic file of any city or town located in it. The Andean zone currently consists of sub zones with low population density, so there is not much information available on its characterization or that of its housing stock.

In addition, it was decided to incorporate into the study the cities in which complementary thermal insulation instruments are applied within the framework of the Atmospheric Decontamination Plans[2] (ADP), with the aim that this study also contributes with base information for the localities, in which, it is tried to diminish the energy requirement of the population and to reduce the emissions of particulate material. For this reason, in the case of the interior central and interior south climatic zone, two cities were considered for analysis.

---

[2] Atmospheric Decontamination Plans are an environmental management instrument that aims to recover environmental quality levels and thus safeguard the health of the population by reducing the diseases associated with such pollution. This regulation applies to the cities of Chillán, Coyhaique, Osorno, Temuco and Valdivia, which have been declared as zones saturated with Respirable MP10 particulate matter and fine MP2.5 particulate matter.

Based on the conditions and criteria described above, it was decided to carry out simulations considering the climatic data of ten cities (Antofagasta, Calama, Copiapó, Valparaíso, Santiago, Chillán, Temuco, Valdivia, Osorno and Coyhaique) that are located within the climatic classification proposed by the NCh 1079 (Figure 1). Figure 1 additionally includes the proposed international classification in Köppen equivalent to the climate of the relevant localities in each zone, with the aim of facilitating the transferability and reuse of the results of this study to other regions of the world with similar climatic conditions.



	Climate zones based on NCh 1079 [25].	Equivalent climatic zones in Köppen based on [26].
🟨	NL North Coast	BWm: Desert with abundant clouds
🟥	ND North Desert	BWk': Cold Desert
🟧	NVT North Transverse Valleys	BWk: Normal Desert
🟩	CL Central Coastal	Csbn: Warm temperate with winter rains and high cloud cover
🟪	CI Central Inside	Csb: Warm temperate with winter rains
🟩	SL South Coast	Cfsb: Rainy with Mediterranean influence
🟦	SI South Inside	
🟦	SE South Extreme	Cfc: Temperate cold rainy without dry season
🟫	An Andean	ETH (w): Height effect tundra with summer rainfall

Figure 1: Housing climate zones in Chile based on NCh 1079 [25] and equivalent zones in Köppen based on "Annual Environment Report 2017"[26].

2.2 Design of the typical Dwelling

The type of housing used in the study was designed based on the statistical studies carried out on existing constructions in Chile and the applicable building regulations. The regulations that mainly conditioned the architectural design and thermal conditioning of the dwelling were:

The General Ordinance on Urban Planning and Construction[3] (OGUC), NCh 1079 and ADP [27][28][29][30][31]. For the architectural design of the typical dwelling, the statistics on the Chilean housing stock allowed to define the type and size of the dwelling; the thermal design was based on the building regulations in Chile.

2.2.1 Architectural Design

Chile's housing stock is made up of 72.5% of one-story buildings [32]. Of the total number of building units in existence up to 2010, 37.8% are single houses and 36% are semi-detached. In addition, it is known that until 2016, 60% of approved construction in Chile was in buildings with a living area of between 36 and 70 m^2 [33]. For this reason, the type of house considered in this study for Chile, is a one-story building with a living area of 70 m^2. The architectural design of the floor plan of the house (Figure 2) was based on the "Typology 1" proposed in a study requested by the Ministry of Energy of the Government of Chile in 2010 [32]. This typology considered a windows-to-wall ration (WWR) of 12% and was used because it was adapted to the characteristics previously established for a representative house in Chile.

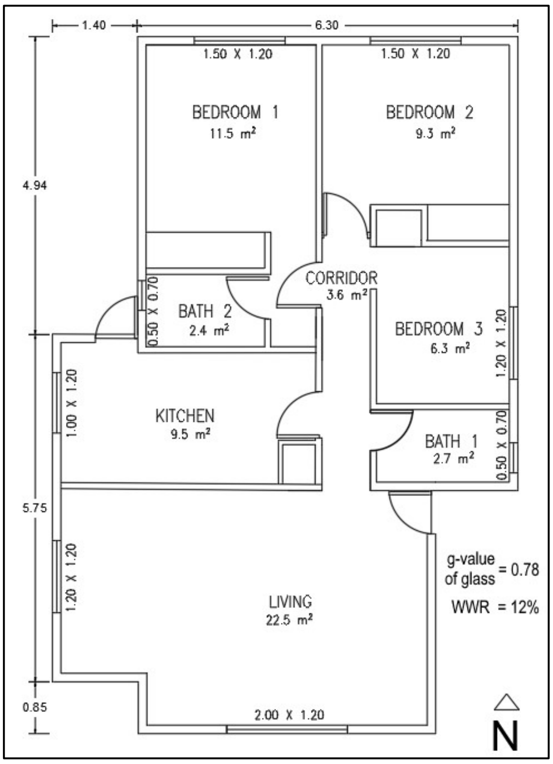


Figure 2: Type of housing based on a study requested by the Ministry of Energy of the Government of Chile (Corporación de Desarrollo Tecnológico) [32].

---

[3] It contains the regulations of the *General Law of Urbanism and Constructions* [34], which establishes technical design regulations and regulates administrative procedures, urban planning processes, land urbanization and construction.

The structure of the house is built on a concrete floor slab, as more than 89% of the houses in Chile use this floor construction solution [32]. With respect to the walls, they will be made up of two layers: 1) construction material towards the interior of the house and 2) thermal insulating material on the exterior side (Figure 3). For the construction material, a thickness of 14 cm was established simulating the width of a brick, due to the fact that the largest number of houses built in the country are made of masonry [32]. It should be clarified here that a specific material for walls was not defined, since the objective of this study is to determine the degree of influence of the different physical properties that define TI (λ, ρ, C_p) in parametric form. In this case the physical properties that define TI (λ, ρ, Cp) will be considered as "design variables".

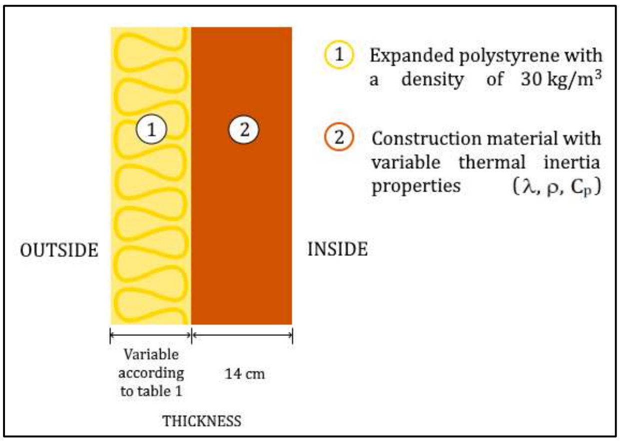


Figure 3: schematic of wall configurations of the type of housing.

2.2.2 Thermal Conditioning Design

For the thermal design, the regulations ADP [27][28][29][30][31], NCh 1079 [25] and OGUC [35] were considered. It was noted that these regulations differ in regards to the thermal insulation requirements of a building and the maximum thermal transmittance (U_{max}) of its component elements [36]. This is due to the fact that NCh 1079 and OGUC have a different climatic and thermal zoning for Chile and that only in certain cities are ADPs in force. For this reason, this study established the use of thermal transmittance values (U) of walls, roofs and windows according to the one that presented strictest requirement for each city (i.e the lowest thermal transmittance).

The thermal insulation of the walls and roof of the typical dwelling was defined in such a way that it complied on its own with the maximum transmittance required by the most restrictive of the three aforementioned regulations applied to each city. Thus, it was not necessary to condition the properties of the wall to meet these thermal requirements. The insulating material used for the walls was expanded polystyrene (λ 0.035 W/mK) of high density (30 kg/m^3) and in the case of the ceiling, glass wool (λ 0.036 W/mK and ρ 160 kg/ m^3). The thickness of the material was established according to the different cities of the study (Table 1).

Additionally, table 1 shows the Heating Degree Days (HDD) required for each city. The HDDs were calculated with respect to activating the heat at a temperature of 15°C, just as they were calculated in the current Chilean regulations. The Cooling Degree Days (CDD) are not mentioned because the median temperatures for all the cities studied do not exceed 21°C.

Table 1

Maximum thermal transmittance (U_{max}) stipulated in the Chilean regulations and the one used in the house type for walls and roof according to climatic zone and city.

		Thermal insulation of walls			**Roof thermal insulation**		
CITY	**Climatic classification according to NCh 1079 [25]**	**U_{max} $[W/m^2 K]$**	**Insulation Thickness [m]**	**U Housing Type $[W/m^2 K]$**	**$U_{maáx}$ $[W/m^2 K]$**	**Insulation Thickness [m]**	**U Housing Type $[W/m^2 K]$**
Antofagasta HDD=141	NL North Coast	2,0 (1)	0,02	**1,35**	0,8 (1)	0,05	**0,65**
Calama HDD=1050	ND North Desert	0,5 (1)	0,07	**0,46**	0,4 (1)	0,10	**0,34**
Copiapó HDD=432	NVT North Transverse Valleys	0,8 (1)	0,04	**0,76**	0,6 (1)	0,06	**0,55**
Valparaíso HDD=532	CL Central Coastal	0,8 (1)	0,04	**0,76**	0,6 (1)	0,06	**0,55**
Santiago HDD=863	CI Central Inside	0,6 (1)	0,06	**0,53**	0,47 (3)	0,08	**0,42**
Chillán HDD=1175		0,45 (2)	0,08	**0,41**	0,28 (2)	0,14	**0,25**
Valdivia HDD=1486	SL South Coast	0,40 (2)	0,09	**0,37**	0,28 (2)	0,14	**0,25**
Temuco HDD=1434	SI South Inside	0,45 (2)	0,08	**0,41**	0,28 (2)	0,14	**0,25**
Osorno HDD=1644		0,40 (2)	0,09	**0,37**	0,28 (2)	0,14	**0,25**
Coyhaique HDD=2514	SE South Extreme	0,35 (2)	0,10	**0,33**	0,25 (2)	0,14	**0,25**

[1] Maximum values of U based on NCh 1079 [25].
[2] Maximum values of U based on Atmospheric Decontamination Plan of the corresponding city [27][28][29][30][31].
[3] Maximum values of U based on the General Ordinance on Urban Planning and Construction [35].
HDD = Heating Degree Days, calculated with respect to a temperature of 15°C for the activation of the heating.

The windows considered for the type of dwelling consist of a PVC frame and double glazing with an air chamber, with the exception of Coyhaique which used argon, in order to comply with the requirements of the NCh 1079 and ADP regulations. Here it is observed that the OGUC is not restrictive for window design, since it does not stipulate maximum transmittance, but rather maximum percentage of glazed surface according to geographic orientation. The typical dwelling complies with these percentages as it was considered in the architectural design stage. Table 2 specifies the glass thicknesses, air chamber and window transmittance (U_g) complying with regulations in each city. The solar factor (g) considered for the windows (g = 0.78) represents a double-glazed window with air gap. Due to solar gains, a variation in ±1% of the g-value can influence the energy demand by up to 0.1% [37]. However, in the study the g-value was constant for all the simulations, since the study was focused on the opaque components of the house.

Table 2

Thermal transmittance of windows (U_g) required by the Regulations and those used in the typical dwelling.

CITY	Climatic classification according to NCh 1079 [25]	Maximum value Ug [W/m^2 K]	Glass thickness [mm]	Thickness air chamber [mm]	Ug Window Housing Type [W/m^2 K]
Antofagasta	NL North Coast	5,8 (1)	4	6	**3,1**
Calama	ND North Desert	3,0 (1)	4	8	**2,9**
Copiapó	NVT North Transverse Valleys	3,0 (1)	4	8	**2,9**
Valparaíso	CL Central Coastal	3,0 (1)	4	8	**2,9**
Santiago	CI Central Inside	3,0 (1)	4	8	**2,9**
Chillán		3,6 (2)	4	8	**2,9**
Valdivia	SL South Coast	3,6 (2)	4	8	**2,9**
Temuco	SI South Inside	3,6 (2)	4	8	**2,9**
Osorno		3,6 (2)	4	8	**2,9**
Coyhaique	SE South Extreme	2,4 (1)	10	20 (argon)	**2,5**

[1] Maximum values of U based on NCh 1079 [25].

[2] Maximum values of U based on Atmospheric Decontamination Plan of the corresponding city [27][28][29][30][31].

2.3 Energy Simulations

The environmental and energy simulations were performed in EnergyPlus, after creating the geometry of the building in DesignBuilder. This choice is due to the fact that it is possible to work with the EnergyPlus calculation engine, which allows simulations to be developed using climate files in an existing database and in turn provides results relating to thermal comfort. In addition, the DesignBuilder [17] and EnergyPlus [13][9] programs have been used in previous thermal inertia studies.

2.3.1 Thermal Inertia Properties

For the energy simulations, new materials were created considering random values of the three design variables thermal conductivity (λ), density (ρ) and specific heat capacity (C_p)for the wall structure of the house.

Random values of the design variables were extracted from a database of actual materials proposed in the "MINVU Bill of Materials" [38]. Among them were materials that were of the same category, but with some differed properties (example: expanded polystyrene with densities between 10 and 30 kg/m^3). However, it was also considered at the time to define the spectrum of existing properties. Metals such as aluminium, copper and zinc were not considered, as their thermal conductivity and density were too high and represented outliers, making it impossible to use them in energy simulation software.

The dispersion range of the properties consisted of 98 values for each design variables respectively. The ranges and frequency with which these physical characteristics of the construction materials considered in this study are found are represented in Figure 4.

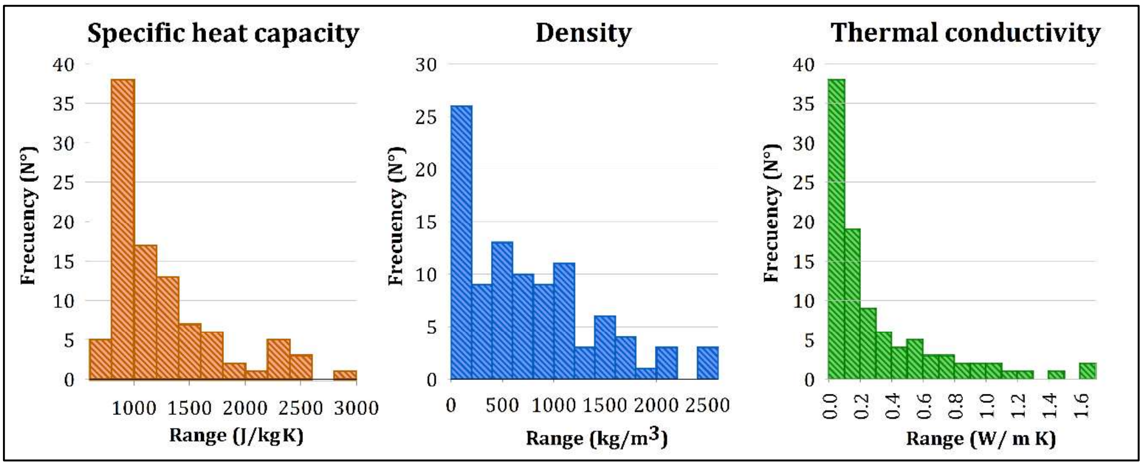


Figure 4: Variation ranges of the physical properties that determine thermal inertia: specific heat capacity in J/kg K, density in kg/m^3 and thermal conductivity in W/m K.

Figure 4 shows that the properties of the existing materials vary in the following ranges: specific heat capacity between 750 and 2800 J/kg K, density 10 and 2500 kg/m^3 and thermal conductivity between 0.025 and 1.63 W/m K. Considering these ranges, it was possible to assign random values to the different properties to perform the simulations.

2.3.2 Number of Simulations per City

Considering the ten cities and the combination of the three variables that define TI, it was determined that it was necessary to carry out 1,474,400 simulations, which would require a computational of time.

In order to reduce the number of simulations, the software Design-Expert was used, which was specialized in experiment design and process optimization. It was estimated that to have statistical significance, as provided by an ANOVA[4] analysis, it was necessary to perform a minimum of 32 tests per city.

On the other hand, Design-Expert was useful to analyze the results of the simulations, because this program allows the identification of the most influential factors in the output variables and the interactions between them. Here the surface response method was used for the optimization of the design variables (λ, ρ, C_p) which in this work was to minimize the annual degrees outside the comfort zone.

2.3.3 Assumptions for the Base Case

In addition to the definition of the typical dwelling and climate data, it was necessary to define parameters relating to the behaviour and use of the building for energy simulations. For this

---

[4] Analysis of Variance (ANOVA) assesses the importance of one or more factors by comparing the means of the response variable at different factor levels.

reason, the conditions of a "base case" were established. In the base case, it was assumed that the typical dwelling will not consider internal energy gains associated with the occupants' behaviour. It was also estimated that the house will not have an air conditioning system (heating or cooling), occupation density, mechanical ventilation, electrical appliances and lighting. In order to study exclusively the TI of the material and the climates, the variables associated with thermal comfort were reduced to the operative temperature.

2.4 Optimization

To determine the variation in the TI characteristics and the number of simulations to be carried out for each climatic zone, the statistical program Design-Expert was used. A total of 32 annual simulations were performed for each city in the DesignBuilder software and the temperature values outside the thermal comfort range (TOTCR) were recorded based on the operational temperature inside the house (Figure 5). Subsequently, the results were entered into Design-Expert in order to identify the optimum combinations values of the design variables that allow to minimize the degrees outside the thermal comfort zone (18-24 °C).

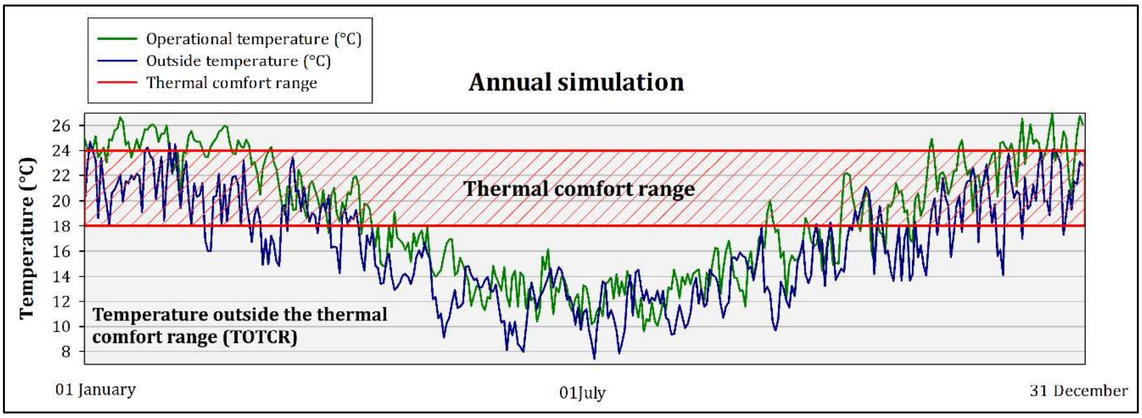


Figure 5: example of annual simulation results of operational and outside temperature in DesignBuilder to quantify the annual sum of operative temperature exceeding the thermal comfort range (18°C and 24 °C).

For each combination of properties defining TI, the hourly operative temperatures were obtained from the energy simulations (Figure 5) and used to calculate the daily difference between any temperatures outside the thermal comfort range (TOTCR) and the base temperatures (T_b). The annual summation of these degrees was made for each of the 32 simulations and this action was repeated for the 10 cities in the study. Here, the combination of thermal conductivity, density and specific heat capacity was considered optimal in case of minimum annual degrees of temperature outside the thermal comfort zone. The calculation of the TOTCR was carried out using the equation (1).

$$TOTCR_a = \sum_{i=1}^{8760} (T_b - To_i) \cdot \chi_c \tag{1}$$

Where:

$TOTCR_a$: Annual degrees of temperature outside the thermal comfort range [Ka].

T_b : Base temperature [°C].
To_i<18 °C the base temperature will be equal to 18 °C.
To_i>24 °C the base temperature will be equal to 24 °C.

To_i : Operative temperature [°C].

χ_c : Correction factor [-].
To_i<18 °C the correction factor will be equal to 1.
$18\ °C \leq To_i \geq 24\ °C$ ° the correction factor will be equal to 0.
To_i>24 °C the correction factor will be equal to -1.

2.5 Sensitivity analysis and comparison with existing materials

In order to quantify the degree of influence of the design input variables (λ, ρ, C_p) on the output variable (Degrees <18°C and >24°C) a sensitivity analysis was performed.

The approach of the analysis was one-to-one, meaning that the input variables were changed one at a time, while the other input variables remained constant to their average value. Due to that, the input variables had different units of measurement, and a normalized sensitivity coefficient was calculated. The input variables would be changed according to a defined percentage, which in this case was ±10%. The simulation was carried out for each change in the input variables and the results were used to calculate the normalized sensitivity coefficient (Si,j). In a sensitivity analysis a higher sensitivity coefficient (Si,j) implies a greater influence of the input variable on the output variable.

Additionally, in order to evaluate and theoretically compare the performance that a construction material with optimal IT properties would have in comparison with existing materials, the annual sums of degrees outside the range of thermal comfort that would be obtained with the material with optimal IT properties and existing materials (reinforced concrete, brick, adobe, pinewood and lightweight concrete) were quantified. The comparison was developed for the cities with the greatest number of degrees outside the thermal comfort range for each climate category, being in this case Calama (desert), Chillán (warm temperate) and Coyhaique (rainy).

3.0 RESULTS

The results show that only a limited number of properties associated with TI had an effect on reducing annual hours of operative temperature outside the comfort zone (Figure 5). In the Design-Expert program, combinations of properties are displayed that allow a minimum of degrees to be set outside the thermal comfort range. With respect to the minimum value of annual degrees outside the comfort zone obtained by the optimal combination, a tolerance of ±1 Ka was considered, which allowed other combinations of properties to be defined as optimal. The need for more than one optimal combination made it possible to establish optimal ranges for each of the three properties in each city and general ranges for each property considering all the cities in the study. The purpose of establishing ranges instead of a single optimal value was to give flexibility to the design variables (λ, ρ, C_p) in order to materialize an optimal TI.

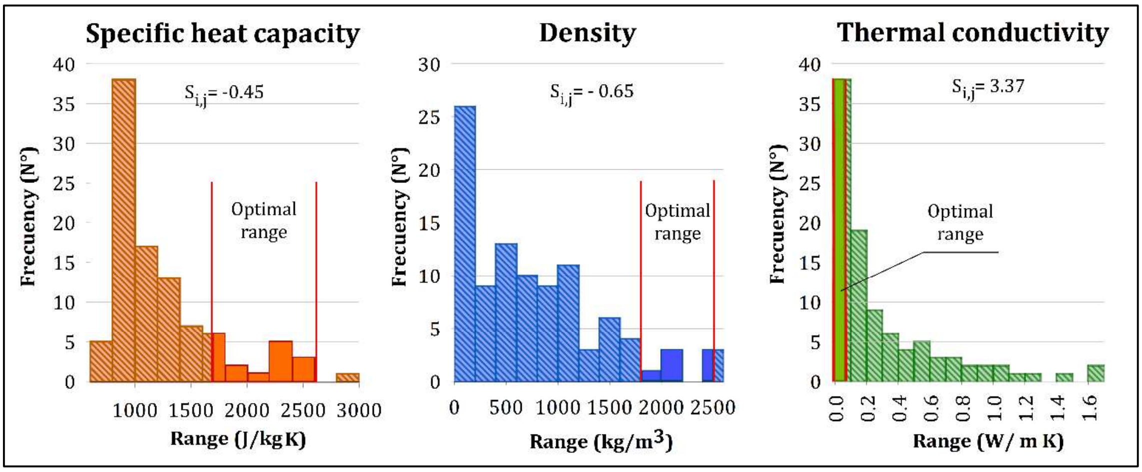


Figure 6: Optimal ranges of physical properties determining thermal inertia; specific heat capacity in J/kg K, density in kg/m^3 and thermal conductivity in W/m K.

Figure 6 shows that the optimal specific heat capacity and density ranges are wider than the thermal conductivity ranges. The optimal range of specific heat capacity is the broadest between 1707 and 2805 (J/kg K) equivalent to the specific heat capacity of 18% of the total materials on the list used. The optimal density range is 8% of the 98 values used and varies between 2500 and 1871 (kg/m^3). In the case of optimal thermal conductivity, the results show that it is limited to a narrow range between 0.025 and 0.03 (W/m K) corresponding to only 5% of materials. It is gathered from these results that, for all cases, the optimal thermal conductivity is the lowest possible regardless of the climate. With respect to specific heat capacity and density, variations were observed in the optimal ranges for each city. In that sense it is concluded that the determination of the optimal range for these properties is dependent on the type of climate.

Additionally, Figure 6 shows that the most influential variable is thermal conductivity ($S_{i,j}$ =3,37) followed by density ($S_{i,j}$ =0,64) and the least influential being specific heat capacity ($S_{i,j}$ =0,45). It follows that the specific heat capacity variation does not significantly affect the output variable. Based on the sensitivity analysis, the annual grades outside the thermal comfort range are shown below, depending on the most influential variables (λ and ρ) in the different climates.

Due to the similarity of both climates and the results obtained for some cities in the study, the optimal properties of thermal conductivity and density were grouped into three macro-climate categories defined in Köppen. The cities of Antofagasta, Calama and Copiapó were grouped for the type of desert climate (BW) (Figure 7). The cities Valparaíso, Santiago and Chillán were grouped in warm temperate climate (Cs) (Figure 8) and Valdivia, Temuco, Osorno and Coyhaique were grouped in rainy climate (Cfs) (Figure 9). The results of the optimal thermal conductivity and density properties shown below are from those cities that represent the broadest range for each climate group. In addition, existing materials (reinforced concrete, lightweight concrete, pinewood, brick and adobe) were added to each figure to facilitate understanding of the results.

Figure 7 shows the results for desert climates. Here it is observed that the optimal ranges of thermal conductivity are delimited between 0.025 and 0.03 W/m K without modifications for the three cities of this type of climate. On the other hand, it is observed that the density ranges are between 2000 and 2500 kg/m^3 varying according to the city or sub-climatic zone. The broadest density range of this category is registered for Antofagasta city (Desert with abundant clouds BWm) between 2007 and 2498 kg/m^3 (Figure 7), followed by Calama (Cold Desert BWk') with optimal densities between 2018 and 2500 kg/m^3 and Copiapó (Normal Desert BWk) with higher densities between 2115 and 2500 kg/m^3.

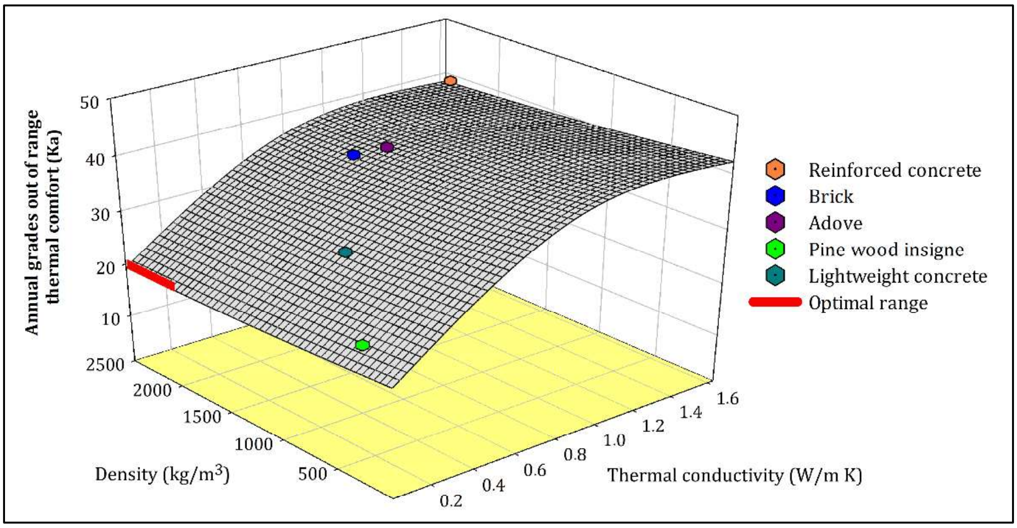


Figure 7: Density and optimal thermal conductivity for desert climate (BW), Antofagasta.

For all cities of the warm temperate climate type it is observed that the optimal range of thermal conductivity is maintained between 0.025 and 0.03 W/m K. However, despite being of the same climate category (warm temperate with Csb winter rains), there are variations in the results of the cities of Santiago and Chillán where the optimal density ranges fluctuate between 1951 and 2494 kg/m^3 and 2129 and 2498 kg/ m^3 respectively, being that the city of

Chillán is the one that presents the narrowest optimal density range for warm temperate climates. On the other hand, Valparaíso (warm temperate climate with winter rains and high Csbn cloud cover) contains the broadest optimal density range between 1871 and 2500 kg/ m³. Based on these results it can be concluded that, although two or more cities are classified in the same climatic category or zoning (example: Santiago and Chillán), they will still have variations in their optimal density if the ambient temperature is different.

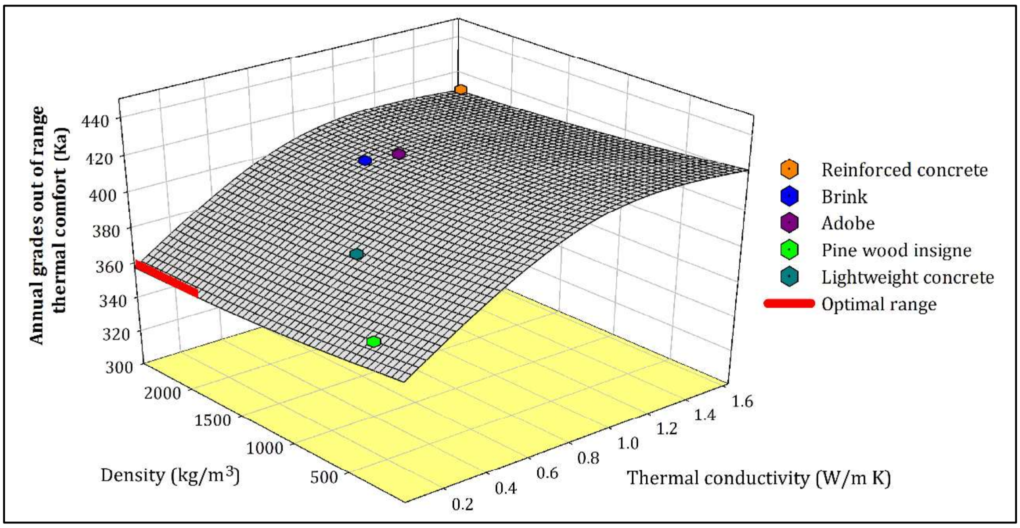


Figure 8: Density and optimal thermal conductivity for warm temperate climate (Cs), Valparaiso.

Rainy climates have the highest optimal density ranges (between 2160 and 2500 kg/ m³) and the city with the narrowest density range between 2422 and 2500 kg/ m³ for Valdivia (rainy with Mediterranean influence Cfsb). Valdivia, Temuco and Osorno are classified with the same type of climate (rainy with Mediterranean influence Cfsb), while Temuco and Osorno are classified in the same climatic zone (interior South), however, their optimal density ranges are different, being between 2163 and 2500 kg/ m³ for Temuco and between 2375 and 2499 kg/ m³ for Osorno. In the case of Coyhaique (temperate cold rainy without dry season Cfc) the optimal density is between 2368 and 2500 kg/ m³. Referring to these cities, although they do not coincide in their optimal density ranges, the same range of optimal thermal conductivity between 0.025 and 0.03 W/m K is observed.

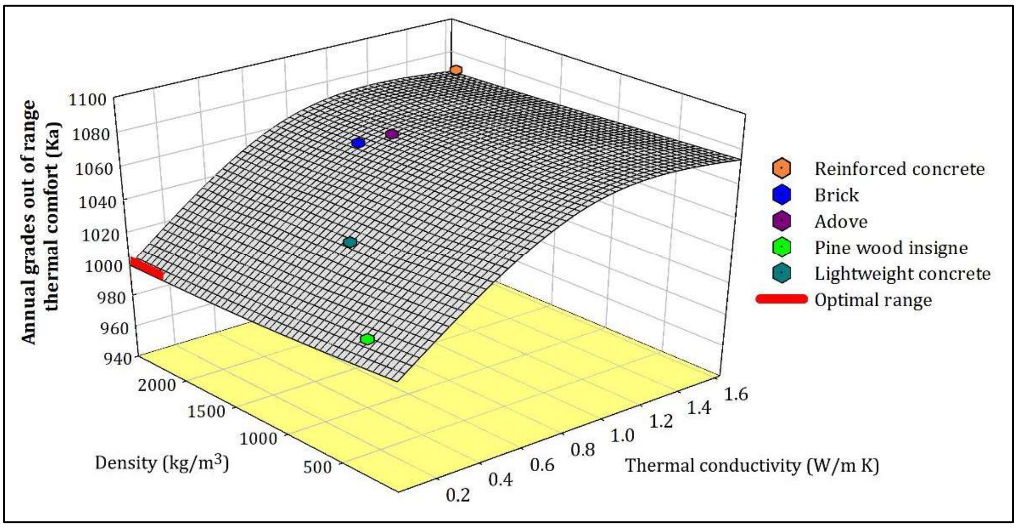


Figure 9: Density and optimal thermal conductivity for rainy weather (Cfs), Temuco.

In general, it is observed that the range of thermal conductivity is limited to 0.025 and 0.03 (W/m K) being considered optimal to the lowest possible for all cases independent of climate. However, the determination of the optimal density is highly climate dependent. For all the cases studied the highest value of optimal density coincides (2500 kg/m^3), while the minimum value of the optimal range varies with respect to the climate. For the rainy climate type (Cf), there is a higher density and a narrower range (2163 and 2500 kg/m^3). Therefore, high density materials should be used in rainy (Cf) climate types. Based on exposed results it can be deduced that a construction material could have the same thermal conductivity and specific heat capacity, varying its density depending on the climate. Furthermore, densities close to 2500 kg/m^3 would have an adequate performance regardless of the climate.

4.0 **DISCUSSION**

The results shown in the previous chapter were obtained on the basis of energy simulations performed in DesignBuilder. Although the energy simulations allow one to predict the thermal performance of a building, the results may differ from reality due to the assumptions chosen in the methodology [10], such as the input parameters describing the characteristics and operation of the building [39].

On the other hand, several studies [40-42] have compared simulation with measurements, stating that there is a strong correlation between both [40][41]. For example, Fathalian and Kargarsharifabad (2018) showed that the differences between real energy consumption and simulation may be less than 1.6% [42]. Some authors argue that the differences are a consequence of parameters that are not easily detected experimentally (sensor measurement error, infiltration flows) [40] and that the closeness of the results to reality will depend on how similar the simulated building is in terms of climate and construction data [39].

Consequently, it is necessary to approach the simulations with the minimum number of key parameters having the highest influence on the simulation results. In this sense, in this paper the number of variables within the simulations were limited to avoid errors in the results (heating or cooling systems, occupation density, mechanical ventilation, electrical appliances and lighting were not considered, see section 2.3.3). Additionally, it identifies that the validation of the results obtained theoretically represents an aspect to be addressed in future research.

Table 3 shows the sum of the annual Temperatures Outside the Thermal Comfort Range (TOTCR) obtained with the optimal material and the other five existing materials (reinforced concrete, brick, adobe, pinewood and lightweight concrete). Two sub-columns are included in the columns of each existing material. One subcolumn refers to the TOTCR result using the respective material and a subcolumn called "reduction". In the column called reduction, the percentage of reduction that would be obtained in the TOTCRs is indicated, considering that the material with optimal thermal inertia characteristics is used in comparison to the material considered in each main column.

Table 3

Annual degrees of temperature outside the thermal comfort range

City	Type of climate	TOTCR [1] with optimal thermal inertia (K)	Reinforced concrete		brick		Adobe		Insigne pine wood		lightweight concrete	
			Degrees of TOTCR (K)	Reduction (%)	Degrees of TOTCR(K)	Reduction (%)	Degrees of TOTCR (K)	Reduction (%)	Degrees of TOTCR (K)	Reduction (%)	Degrees of TOTCR (K)	Reduction (%)
Calama	**Desert**	**562**	640	12,1	635	11,4	639	12,1	577	2,4	606	7,3
Chillán	**Warm temperate**	**970**	1043	7,0	1040	6,7	1044	7,0	988	1,7	1014	4,3
Coyhaique	**Rainy**	**1940**	2043	5,0	2038	4,8	2043	5,1	1958	1,0	1999	2,9

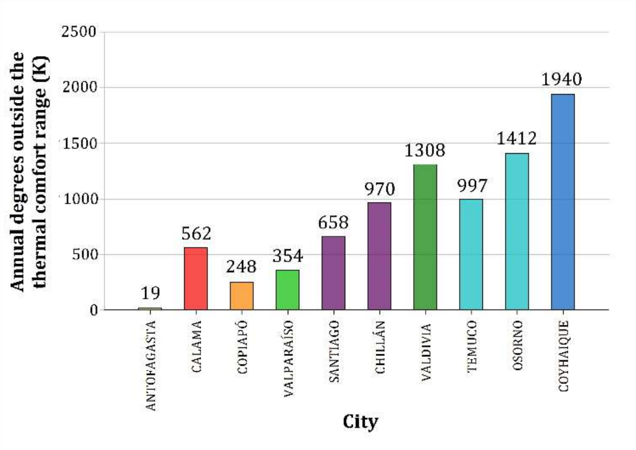
[1] Temperature outside the thermal comfort range

The comparison shows that the average percentage of temperature reduction outside the thermal comfort range is higher for Desert climates (9.05%), followed by Warm temperate climates (5.35%) and in rainy climates the lowest percentage (3.75%). Consequently, it is in desert climates that optimal TI should be sought, as greater profits would be achieved.

In all three climates the lowest percentage of temperature reduction outside the thermal comfort range with respect to the optimal TI material is obtained with the use of solid wood (up to 1%). However, there is currently no such solid wood construction system on the market in Chile. In its defect, of the existing constructive systems commercialized, it is deduced that the use of lightweight concrete is the most suitable if it is desired to generate a positive effect in the thermal comfort (up to 3%). Conversely, it would be less favourable to use reinforced concrete or adobe, since it presents the highest percentage of temperature reduction outside the thermal comfort range with respect to the optimal TI material (up to 12%).

Another observation is that despite being materials with different properties, reinforced concrete and adobe for all climates present similar temperature values outside the range of thermal comfort with respect to the optimal TI material. It is therefore inferred that, although the λ, ρ and C_p are different between the materials, they may exhibit similar behaviour depending on the combinations of their material properties.

On the other hand, with the Design-Expert program, it was possible to estimate the annual degrees outside the thermal comfort zone for each city if the optimal values of λ, ρ and C_p were used (Figure 10).



CITY	Optimal thermal conductivity W/m K	Optimal density kg/m^3	Optimal specific heat capacity J/kg K
ANTOFAGASTA	0.025	2007	2671
CALAMA	0.025	2500	2780
COPIAPÓ	0.025	2342	2522
VALPARÍSO	0.025	2414	2683
SANTIAGO	0.025	2371	2742
CHILLÁN	0.025	2317	2694
VALDIVIA	0.025	2499	2528
TEMUCO	0.025	2474	2776
OSORNO	0.025	2461	2751
COYHAIQUE	0.025	2368	2221

Figure 10: Annual grades outside the thermal comfort range for the cities in the study using the combination of optimal properties.

It is observed that in desert climates (Antofagasta, Calama, Copiapó) the annual degrees outside the thermal comfort zone are between 19 and 562 Ka. The results show that for the Desert climate (BWm) the TOTCR can be lower than 50 Ka which would imply that if the thermal performance of those houses is optimized considering other passive measures (better orientation, greater internal gains, optimization of thermal insulation or night ventilation) could have an energy consumption of heating equal to zero. This conclusion is consistent with other studies [12][15][14] which mention that the combination of TI and other strategies for saving or efficient use of building energy can improve the energy performance of dwellings.

Considering the above, Antofagasta dwellings could dispense with a heating system if the thermal performance were optimized due to the fact that their average minimum temperature is 14 °C and the average maximum is 24°C. In addition, it is possible to observe the variations between the different Desert climates with respect to the annual degrees outside the range of thermal comfort, such as Desert with abundant clouds (Antofagasta, 19 Ka), Cold Desert (Calama, 562 Ka) and Normal Desert (Copiapó 248 Ka).

For warm temperate climates (Valparaíso, Santiago, Chillán) the TOTCR between 354 and 970 Ka, establishing a variation of 312 Ka, for the cities of Santiago and Chillán classified in the same interior central climatic zone and with warm temperate climate with winter rains (Csb). The variation in degrees is due to the geographical differences between these two cities, despite being classified in the same climatic zone.

The annual degrees outside the range of thermal comfort in rainy climates are between 997 and 1940 Ka, being the climatic zone in which a heating system is most necessary, because in these cities most of the annual degrees of thermal discomfort are under the range of comfort. There is a difference of 415 Ka between Temuco and Osorno, cities classified in the southern interior and with a rainy climate with Mediterranean influence (Cfsb). This may be due to geographical differences that make the temperature of Temuco much warmer than Osorno (located farther south in Chile).

The results obtained show variations in the optimal density ranges for cities classified in the same climate zoning (Nch 1079) and Köppen classification for example in the cases of Santiago-Chillán (658 and 970 Ka) and Temuco-Osorno (997 and 1412Ka). While a range of optimal density can be established in common, such variations suggest that in climate classifications covering large geographical areas, the results may not be transferable between cities belonging to the same climate classification.

As in this work, there are numerous studies that refer to climate zones, analyzing only one city that represents them [12][43-47]. In some studies, there are actually specific case studies of buildings located in representative cities of a determined country [12][45][47]. These have been concluded that the results obtained with existing programs for each city [43][45-47] can be transferable to buildings in similar climatic conditions [47].

The climate classifications are structured according to common general characteristics [8]. For example the Köppen classification, is based on temperature and aridity levels. Authors such as Thornthwaite consider additionally the humidity and potential evapotranspiration and H. Flohn created a classification based on factors related to the atmospheric circulation of the main winds [8]. Here is observed that the climate classifications consider different climate factors (temperature, aridity, humidity, atmospheric movements) and also induces deferent characterizations. Consequently, it is expected that there are variations within the same macro-climate classification, since the climatic zones do not necessarily represent the particularities of the microclimates existing within them, defined according to the determined climatic classification.

In this work, differences within the same Köppen climate classification were observed for the optimum values of density and Specific heat capacity. In the case of Temuco-Osorno (Cfsb), the optimal values of density varies between 0.5% and Specific heat capacity 0.9%. For the cities Santiago and Chillan, which belong to the same climatic zone (Csb), the variations for density and Specific heat capacity of 2.3% and 1.8% are respectively obtained.

The results referring to the use of macro-climate classifications presented in this work suggest that there may be variations in the optimal values of the thermal inertia characteristics of specific heat capacity and density. However, it is expected that the variations in the optimal characteristics of specific heat capacity and density will not exceed 3%.

In this study the optimal TI was evaluated, considering only thermal comfort as an output variable. Therefore, it is suggested to continue this work with the evaluation of TI together with other energy optimization measures such as ventilation, insulation, housing orientation, shape coefficient, breaking of thermal bridges, among others, in order to determine if these can contribute even more to the reduction of temperature hours outside the range of thermal comfort. On the other hand, here a fixed wall thickness (14 cm) was considered to configure a representative house of the Chilean housing stock, so it is suggested to carry out more research that considers the optimization of the wall thickness with the optimal properties of TI exposed in this work.

5.0 CONCLUSIONS

This study determines the optimal TI with respect to the operative temperature range for thermal comfort (18 and 24°C), considering a typical house located in different climatic zones of Chile. Here, energy simulations were carried out for a typical dwelling in DesignBuilder followed by sensitivity analysis and optimisation. The climatic data of 10 cities belonging to different climatic zones of Chile were considered and the physical properties that determine the TI (λ, ρ, C_p) were varied in order to find optimal combinations.

The results of the sensitivity analysis show that, with respect to the thermal comfort temperature range, the most relevant TI property is the thermal conductivity ($S_{i,j}$=3,37) and the least influential is the specific heat capacity ($S_{i,j}$=0,45). From the optimization, it is observed that the range of optimal thermal conductivity does not depend on the type of climate, since for all cases it is limited to 0.025 and 0.03 (W/m K) with the lowest possible optimum being considered. However, there are variations with respect to the effect of climate on optimal density. For desert climates (BW) the optimal density varies between 2007 and 2500 kg/m^3, for warm temperate climates (Csb) between 1871 and 2500 and for rainy type (Cf) it is the narrowest range between 2163 and 2500 kg/m^3. Consequently, the choice of a material with optimal properties for thermal comfort can be based on its thermal conductivity, being the minimum possible, and its density, which would have an optimal performance with values close to 2500 kg/m^3.

It follows that the thermal characteristics of the optimal material must have a similar thermal conductivity to that of expanded polyurethane (0.025 W/m K) or expanded polystyrene (0.036 W/m K), but the optimal density should be as the density of a brick (1800 kg/m^3) for warm temperate climates, clay (2100 kg/m^3) for desert climates and reinforced concrete or vibrated mass (2400 kg/m^3) for all climates, especially the rainy climate which requires a higher density. There is currently no known material with these characteristics, since those with optimal densities have very high thermal conductivity (example. Concrete 1.63 W/m K) and materials with low thermal conductivity are insulation materials with low density (example. Polyurethane 25 to 70 kg/m^3).

This study shows that TI affects thermal comfort in all the climates analysed here (Desert, Warm and Rainy) having a positive effect when optimal values are used. However, the values of the properties that define the TI of existing materials differ from the optimal values. In this sense, this study contributes to developing the theoretical foundation for the creation of new materials with optimal TI characteristics according to the type of climate in which the dwelling is located.

REFERENCES

[1] EIA, Annual Energy Outlook 2016, Energy Information Administration (EIA), USA, Washington DC. 2016.

[2] Shaik S, Yeboah OA. Does climate influence energy demand? A regional analysis. Applied Energy 2018; 212: 691–703.

[3] Pérez-Andreu V, Aparicio-Fernández C, Martínez-Ibernón A, Vivancos JL. Impact of climate change on heating and cooling energy demand in a residential building in a Mediterranean climate. Energy 2018; 165: 63–74.

[4] Cosar-Jorda P, Buswell RA, Mitchell VA. Determining of the role of ventilation in residential energy demand reduction using a heat-balance approach. Building and Enviroment 2018; 144: 508–518.

[5] Justo M, Martin H, Fournier J, Lacarrière B, Le Corre O. Analysis of reduction of energy demands for Zero Emission Renovated Office Building by using thermal mass and ventilative Assessing the feasibility cooling. Energy Procedia 2017;132: 592–597.

[6] Al-Sanea SA, Zedan MF, Al-Hussain SN. Effect of thermal mass on performance of insulated building walls and the concept of energy savings potential. Applied Energy 2010; 89: 430–442.

[7] Adamczyk J, Dylewski R. The impact of thermal insulation investments on sustainability in the construction sector. Renewable and Sustainable Energy Reviews 2017; 80: 421– 429.

[8] M. Allaby. Dictionary of Earth Sciences.3ra ed. Oxford University; 1990.

[9] Aste N, Angelotti A, Buzzetti M. The influence of the external walls thermal inertia on the energy performance of well insulated buildings. Energy and Buildings 2009; 41: 1181–1187.

[10] Verbeke S, Audenaert A. Thermal inertia in buildings: A review of impacts across climate and building use. Renewable and Sustainable Energy Reviews 2018; 82: 2300–2318.

[11] Karlsson J, Wadsö L, Öberg M. A conceptual model that simulates the influence of thermal inertia in building structures. Energy and Buildings 2013; 60: 146–151.

[12] Aste N, Leonforte F, Manfren M, Mazzon M. Thermal inertia and energy efficiency - Parametric simulation assessment on a calibrated case study. Applied Energy 2015; 145: 111–123.

[13] Stazi F, Tomassoni E, Bonfigli C, Di Perna C. Energy, comfort and environmental assessment of different building envelope techniques in a Mediterranean climate with a hot dry summer. Applied Energy 2014; 134: 176–196.

[14] Stazi F, Bonfigli C, Tomassoni E, Di Perna C, Munafò P. The effect of high thermal insulation on high thermal mass: Is the dynamic behaviour of traditional envelopes in Mediterranean climates still possible?. Energy and Buildings 2015; 88: 367–383.

[15] Gagliano A, Patania F, Nocera F, Signorello C. Assessment of the dynamic thermal performance of massive buildings. Energy and Buildings 2014; 72: 361–370.

[16] Di Perna C, Stazi F, Casalena AU, Orazio MD. Influence of the internal inertia of the building envelope on summertime comfort in buildings with high internal heat loads. Energy and Buildings 2011; 43: 200–206.

[17] Evola G, Marletta L, Natarajan S, E. Patanè. Thermal inertia of heavyweight traditional buildings: experimental measurements and simulated scenarios. Energy Procedia 2017; 133: 42–52.

[18] Siddiqui O, Kumar R, Fung A. S, Zhang D, White M. A, Whitman C. A. Modelling for performance prediction of highly insulated buildings with different types of thermal mass. Applied Thermal Engineering 2017; 122: 139–147.

[19] Baetens R, Petter B, Gustavsen A. Phase change materials for building applications : A state-of-the-art review. Energy and Buildings 2020; 42: 1361–1368.

[20] Ar M, Bilgin F, Ni S, Karabay H. PCM integrated to external building walls : An optimization study on maximum activation of latent heat. Applied Thermal Engineering 2020; 165: 114560.

[21] Whiffen T. R, Russell-smith G, Riffat S. B. Active thermal mass enhancement using phase change materials. Energy and Buildings 2016; 111: 1–11.

[22] Nghana B, Tariku F. Phase change material' s (PCM) impacts on the energy performance and thermal comfort of buildings in a mild climate. Building and Environronment 2016; 99:221–238.

[23] Lampe G, Pfeil A, Schmittlutz, R, Tokarz, M. Lüftungs- und Klimaanlagen in der Bauplanung. Wiesbaden: Bauverlag 1974.

[24] ISO 7730: Ergonomics of the thermal environment - Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria 2006: 7730.

[25] INN. NCh 1079 Arquitectura y construcción - Zonificación climático habitacional para Chile y recomendaciones para el diseño arquitectónico, Instituto Nacional de Normalización (INN). Santiago, Chile; 2008.

[26] INE. Medio Ambiente informe anual 2017, Instituto Nacional de Estadísticas (INE). Santiago, Chile; 2017.

[27] MMA. DS N°48 Plan de prevención y descontaminación atmosférica para las comunas de Chillán y Chillán Viejo, Ministerio del Medio Ambiente (MMA). Santiago, Chile; 2016.

[28] MMA. DS N°25 Plan de prevención y Descontaminación Atmosférica para la comuna de Valdivia, Ministerio del Medio Ambiente (MMA). Santiago, Chile; 2017.

[29] MMA. DS N°8 Plan de prevención y Descontaminación Atmosférica para las comunas de Temuco y Padre las casas, Ministerio del Medio Ambiente (MMA). Santiago, Chile; 2018.

[30] MMA. DS N°47 Plan de prevención y Descontaminación Atmosférica para la comuna de Osorno, Ministerio del Medio Ambiente (MMA). Santiago, Chile;2016.

[31] MMA. DS N°46 Plan de prevención y Descontaminación Atmosférica para la comuna de Coyhaique, Ministerio del Medio Ambiente (MMA). Santiago, Chile; 2016.

[32] CDT. Estudio de usos finales y curva de oferta de la conservación de la energía en el sector residencial, Corporación de Desarrollo Tecnológico (CDT). Santiago, Chile; 2010.

[33] INE. Edificación informe anual 2016, Instituto Nacional de Estadísticas (INE). Santiago, Chile; 2016

[34] MINVU. Ley general de urbanismo y construcciones, Ministerio de Vivienda y Urbanismo (MINVU). Santiago, Chile; 1975

[35] MINVU. Ordenanza General de Urbanismo y Construcciones, Ministerio de Vivienda y Urbanismo (MINVU), Santiago, Chile; 1992.

[36] INN. NCh 853 Acondicionamiento térmico - Envolvente térmica de edificios - Cálculo de resistencias y transmitancias térmicas, Instituto Nacional de Normalización (INN). Santiago, Chile; 2007.

[37] Martinez-Soto A. Jentsch M. F. Comparison of prediction models for determining energy demand in the residential sector of a country. Energy and Buildings 2016; 128: 38–55.

[38] MINVU. Listado de materiales, Ministerio de Vivienda y Urbanismo (MINVU). Santiago, Chile, 2007.

[39] Fumo N, Mago P, Luck R. Methodology to estimate building energy consumption using EnergyPlus Benchmark Models. Energy and Buildings 2010; 42: 2331–2337.

[40] Mazzeo D, Matera N, Cornaro C, Oliveti G, Romagnoni P, De Santoli L. EnergyPlus, IDA ICE and TRNSYS predictive simulation accuracy for building thermal behaviour evaluation by using an experimental campaign in solar test boxes with and without a PCM module. Energy and Buildings 2020; 212: 109812.

[41] Mateus N. M, Pinto A, Carrilho G. Validation of EnergyPlus thermal simulation of a double skin naturally and mechanically ventilated test cell. Energy and Buildings 2014; 75: 511–522.

[42] Fathalian A, Kargarsharifabad H. Case Studies in Thermal Engineering Actual validation of energy simulation and investigation of energy management strategies (Case Study: An office building in Semnan, Iran). Case Studies in Thermal Engineering 2018; 12: 510– 516.

[43] Jazaeri J, Gordon R. L, Alpcan T. Influence of building envelopes, climates, and occupancy patterns on residential HVAC demand. Journal of Building Engineering 2019; 22: 33–47.

[44] Mendecka B, Tribioli L, Cozzolino R. Life Cycle Assessment of a stand-alone solar-based polygeneration power plant for a commercial building in different climate zones. Renewable Energy 2020; 154: 1132–1143.

[45] Manu S, Brager G, Rawal R, Geronazzo A, Kumar D. Performance evaluation of climate responsive buildings in India - Case studies from cooling dominated climate zones. Building and Environment 2019; 148: 136–156.

[46] Wang R, Lu S, Feng W. Impact of adjustment strategies on building design process in different climates oriented by multiple performance. Applied Energy 2020: 266: 114822.

[47] Liu C, Xu W, Li A, Sun D, Huo H. Analysis and optimization of load matching in photovoltaic systems for zero energy buildings in different climate zones of China. Jornual of Cleaner Production 2019; 238: 117914.