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Feasibility of PassivHaus standards and alternative passive design on climatic zones of Chile - Determination of energy requirements with dynamic simulation.

Factibilidad de estándares PassivHaus y diseño pasivo alternativo en zonas térmicas de Chile – Determinación de requerimientos energéticos mediante simulación dinámica.

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Cconstructive solutions,
PassivHaus standards,
Chilean building regulations

ABSTRACT

The current building envelope standards from Article 4.1.10 of the “General Law of Urban Planning and Construction” The current building envelope standards from Article 4.1.10 of the “General Law of Urban Planning and Construction” in Chile are applied on a typical residential building for the climate of Concepción (36° Latitude South, 73° Longitude West) and a detailed energy simulation program is used to assess the energy performance of this building. The simulation results of the Chilean standards are then compared with simulation results of PassivHaus standards upon the same building layout and with simulation results from the same typical building when applying alternative passive solar design and envelope upgrade techniques. The research aims to identify useful design strategies for achieving energy results comparable to those proposed by PassivHaus standards (i.e. less than 15kWh/m^2 annum for heating and cooling needs). This would demonstrate to designers, developers and clients how to incorporate cost-effective features and build beyond current regulations in order to achieve large energy savings. In addition, this study is expected to be of use for policy makers, providing suggestions on how future energy regulations of Chile can promote low energy building designs. This study also aims initiate a discussion regarding future methodologies for assessing climate-responsive design in the Chilean context, in a way that useful passive features can also be considered, since they may represent a cost-effective alternative to PassivHaus standards.

Palabras clave:
Eficiencia energética,

RESUMEN

Las normas actuales de construcción para envolvente térmica del artículo 4.1.10 de la "Ley General de Urbanismo y Construcción" en

Ahorro de energía en edificios,
Mejora de la envolvente,
Soluciones constructivas,
Estándar PassivHaus,
Normativa chilena de construcción

Chile son aplicadas sobre una unidad residencial típica, para el clima de Concepción (36 ° de latitud Sur, 73 ° Longitud Oeste). Se utiliza una simulación detallada para evaluar el desempeño energético de dicho edificio. Los resultados de la simulación de las normas chilenas se comparan luego, con resultados de simulación de las normas Passivhaus sobre el mismo diseño de edificio y con resultados de simulación al aplicar alternativas de diseño solar pasivo y mejoramiento intermedio de envolvente térmica. La investigación tiene como objetivo identificar estrategias de diseño útiles para el logro de resultados de desempeño energético comparables a los propuestos por las normas Passivhaus (es decir, menos de 15kWh/m^2 annum para calefacción). Esto demostraría a los diseñadores, desarrolladores y clientes la forma de incorporar características rentables y construir más allá de la normativa vigente a fin de lograr un gran ahorro energético. Además, se espera que el estudio sea de utilidad para los responsables de diseñar la reglamentación, ofreciendo sugerencias sobre cómo éstas pueden promover el diseño de edificios de baja demanda energética. Este estudio también tiene como objetivo iniciar un debate sobre futuras metodologías de evaluación de diseño bioclimático en el contexto climático Chileno, de manera que las características útiles de diseño pasivo también puedan ser consideradas, ya que pueden representar una alternativa rentable.

1. Introduction

The bioclimatic or passive architectural design has become a main stream for achieving energy savings in buildings. Key concepts involved in this approach of passive architectural design are optimal building orientation, solar exposure (in the case of passive solar systems), adequate levels of insulation and thermal storage strategies by the use of thermal mass. Constant research has been ongoing to study the suitability of these strategies to specific climates and their management against time dependence cycles (summer to winter, day to night). In terms of energy-efficiency, the passive design approach has traditionally promoted the use of natural ventilation.

On the other hand, another approach for energy efficient buildings arises from the ideas brought by the PassivHaus Institute of Germany. They suggest that the “bioclimatic” or “passive” design approach on its own is not enough to conceive energy-efficient buildings, because of its strong reliance upon orientation and shape of the building in order to obtain solar gains, plus its reliance on using natural ventilation, which may cause detrimental heat losses. According to the PassivHaus concept, buildings should be conceived through an “active approach” using heavily insulated envelopes achieving highly reduced air-tightness, so that the heating requirements could be met by just pre-heating incoming air mechanically through heat exchangers. It is important to remark that this approach does not discard the use of building integrated renewable energy; however energy efficiency from a PassivHaus design would not rely on the use of such systems (BRE-PassivHaus, 2010).

PassivHaus standards have become popular throughout the central and northern European region where in general, heating requirements are the most important target for energy savings in buildings (Feist et al., 2007). These standards are focused mainly on achieving reduced envelope U-values, disregarding aspects such as strategic use of thermal inertia. In fact, experiences of PassivHaus in central Europe have shown that the effect of internal thermal mass to store solar direct gains is negligible in such regions (Schnieders, 2009). However, in Mediterranean zones from southern Europe where solar energy can become either beneficial in winter or lead to overheating in summer, passive strategies (such as effective use of solar direct gains by using sunspaces, thermal mass for cooling and heating, etc.), have proven to be of significance to ensure thermal comfort (Kolokotroni et al., 1990). The sole use of low U-values required by PassivHaus standards may therefore not be the only design approach to reach PassivHaus energy performance (defined as 15 kWh/m^{2}annum for heating and cooling needs) in more temperate climates, leaving the opportunity to merge PassivHaus standards with the more classic passive architectural approach in such regions.

Chile has committed to follow the path of energy-efficiency by looking towards the regulatory frameworks adopted by countries of the European Union and particularly United Kingdom, Germany and Spain. In a similar way as these European countries, a Thermal Qualification Procedure has been designed by the Chilean Ministry of Housing in association with the National Programme for Energy Efficiency during the past three years (Fissore et al., 2009). This Procedure is going to come into force in 2012 and it aims to implement energy rating labels to all future residential buildings. The Procedure also includes the implementation of its own Simplified Calculation Method, as well as its own alternative Dynamic Energy Design Tool (CCTE_CL 2.0, Bustamante et al., 2007). Such procedures are an important first step to increase the interest of people in energy efficiency of buildings in Chile, and to encourage designers and real-estate developers to add the energy efficiency aspect in their services.

However, the current baseline for benchmarking the energy performance of residential buildings in the upcoming Thermal Qualification Procedure is going to be based on the current building requirements given by the existing General Law of Urban Planning and Construction as implemented in 2007 (OGUC, 2011). These requirements are mainly set by maximum U-values allowed for the different building components, and were a significant technical improvement in building regulations when they were initially released in 2007. However, these requirements may not be sufficiently challenging today to ensure further energy savings in current residential buildings.

Considering the future challenges on the Chilean energy scenario, and the global concern for adopting significant compromises to reduce the energy consumption in buildings, it is found highly relevant to study the potential benefits of implementing internationally recognised building standards such as PassivHaus in Chile. Conversely, it is found interesting to investigate other more flexible passive architectural solutions, as alternative ways for achieving considerable energy savings goals in housing projects.

Therefore, the following paper focuses on assessing the viability of applying PassivHaus standards on housing buildings located in a typical temperate climate (Concepcion, Chile. 36° Latitude South, 73° Longitude West) and comparing their energy performance against the current Chilean standards. In addition, alternative strategies of passive architecture will also be assessed (such as use of passive solar gains, thermal mass and natural ventilation) which, perhaps combined with intermediate envelope standards would minimize energy demand to a similar extent as the PassivHaus requirements but usually at lower cost.

2. Background

2.1 The current Chilean energy regulation

Chile aims to update their energy policies in the following years in order to support the efforts of the country for the reduction of CO_2 emissions and address the issue of the Security of Energy Supply. However the Chilean background would differ in many aspects from countries of the European Union, starting with the differences in climates, technical advancements in construction standards and of course, its economical situation. Fissore et al. (2009) states that in general terms, the average primary energy consumption from a house in Chile complying with the regulatory standards reach 192 kWh/m^{2}annum, whereas an optimal energy consumption could be approximately from 88 kWh/m^{2}annum (assuming generally affordable measures to improve thermal performance) to 40 kWh/m^2 year (assuming currently unaffordable measures for thermal improvements).

According to the Article N° 4.1.10 of the General Law of Urban Planning and Construction (OGUC, 2011), all new Houses would have to comply with requirements of thermal conditioning, according to the heating degree days from the classified seven climatic zones across the country. These requirements for thermal conditioning are given by maximum U-values allowed for the different envelope components, according to climatic zones.

Table 1 shows U-values for opaque components (walls, floors and roofs) whereas Table 2 presents the maximum window to wall ratios allowed by climatic zone. Both tables highlight the requirements for the climatic zone 4 that enclose the typical temperate climate of Concepción.

Table 1: U-values required per climatic zone – Chile. Source: OGUC, 2011
Tabla 1: Valores de U requeridos por zona climática – Chile. Fuente: OGUC, 2011

MINIMUM REQUIREMENTS FOR BUILDING ELEMENTS PER CLIMATIC ZONE ACCORDING TO THE CURRENT CHILEAN THERMAL REGULATION						
Climatic Zone	ROOFS		WALLS		VENTILATED FLOORS	
	U-Value W/m^{2}K	Resistance m^{2}K/W	U-Value W/m^{2}K	Resistance m^{2}K/W	U-Value W/m^{2}K	Resistance m^{2}K/W
1	0.84	1.19	4	0.25	3.6	0.28
2	0.6	1.67	3	0.33	0.87	1.15
3	0.47	2.13	1.9	0.53	0.7	1.43
4	0.38	2.63	1.7	0.59	0.6	1.67
5	0.33	3.03	1.6	0.63	0.5	2
6	0.28	3.57	1.1	0.91	0.39	2.56
7	0.25	4	0.6	1.67	0.32	3.13

Table 2: maximum window percentage per climatic zone – Chile. Source: OGUC, 2011
Tabla 2: porcentaje máximo de ventanas por zona climática – Chile. Fuente: OGUC, 2011

Climatic Zone	Maximum window glazing percentage areas		
	Single Glazing	Double Glazing with Gas Cavity	
		3.6W/m^{2}K $\geq$ U > 2.4W/m2K	U $\leq$ 2.4W/m^2 K
1	50%	60%	80%
2	40%	60%	80%
3	25%	60%	80%
4	21%	60%	75%
5	18%	51%	70%
6	14%	37%	55%
7	12%	28%	37%

Regarding the maximum window-to-wall ratios stated in Table 2, it is important to observe that the Article 4.1.10 describes also an alternative method to comply with the requirements in climatic zones 3 to 7 (coldest zones). In order to account for the possibility of exceeding the maximum allowed window areas, professionals must certify a "Balanced U-Value" through the following equation:

$$\frac{(SW1xU1)+(SW2xU2)+(SW3xU3)+(SGLxUGL)}{\text{Total Surface Area of external facade}} = \text{Balanced U Value}$$

Where:

SW1 to 3 the surface areas of each facade walls
U the correspondent thermal transmittance U-value of the walls
SGL the surface areas of windows
UGL the thermal transmittance U-value of the windows

Values of this balanced U-value must comply with the ones stated in Table 3 according to the specific climatic zone. It can be observed that this alternative methodology addresses to window-to-wall ratio limits in a simplified approach that can incur to unnecessary design restrictions.

Table 3: balanced U-values for the different climatic zones of Chile, alternative method to comply with regulation. Source: OGUC, 2011
Tabla 3: Valores de U balanceados par las diferentes zonas climáticas, método alternativo de cálculo para cumplir con la normativa. Fuente: OGUC, 2011

Zone	Balanced U value W/m^{2}K
3	2.88
4	2.56
5	2.36
6	1.76
7	1.22

2.2 The PassivHaus concept

The PassivHaus Institute during the last decade has helped defining the standards for ultra low-energy construction in buildings. These standards have been gradually introduced across the European community.

The main focus of PassivHaus design is to "dramatically reduce the requirement for space heating and cooling" (BRE-PassivHaus, 2010), which according to the approach of this institute can be achieved without relying on the use of renewable energy technologies and without risking optimal comfort levels.

To achieve the PassivHaus standard, the energy required for space heating must not exceed 15 kWh/m^{2}annum, in order to be met by Heat Recovery technology that is integrated into a Mechanical Ventilation system. Thereby Feist et al. (2005) describe the PassivHaus concept as an integrated approach to achieve energy efficiency and indoor air quality with the controlled injection of pre-heated fresh air.

To ensure this dramatic reduction in the heating load, a PassivHaus building should comply with the following standards:

- Opaque U-Values such as walls, floors and roofs must be less than 0.15 W/m^{2}K.

- U-Values for doors and windows (including frames) must be lower than 0.8 W/m^{2}K, which in the case of windows can be achieved mainly by using triple glazing.

- Thermal bridges should be minimized or ideally eliminated.

- Air-tightness should be less than 0.6 ACH @ 50 Pa.

- The use of mechanical ventilation system integrated to a heat recovery unit with at least 75% efficiency.

In addition, the PassivHaus Institute has developed its own Energy Design tool called “PassivHaus Planning Package – PHPP Tool” (Feist, 2010), which is basically a spreadsheet that treats the whole building as one zone of energy calculation (i.e. modelling only the external envelope area, including floors, ignoring internal partitions) and it combines in its calculation methodology the monthly calculation method for heating and cooling energy requirements from the ISO 13790 Standard (2007) with PassivHaus utilization rate factors that have been systematically calibrated with dynamic simulations and with results obtained from monitoring built PassivHaus examples of the PassivHaus CEPHEUS project (Cost effective PassivHaus as European Union Standards. The building examples were mainly located in Austria, Germany, Switzerland and north of France) (Schnieders et al., 2006).

3. Methodology

In order to study the feasibility of applying PassivHaus standards and alternative passive design techniques for a typical Chilean climate, a detached, single level House layout is assessed (Fig. 1) by using the ESP-r simulation program (Aasem, et al., 1994; Stratchan, et al., 2008) through a set of energy simulations in three stages (Fig. 2). The PassivHaus Planning Package is also used during the second stage of simulations (see figure 2) to support the theoretical assessment of PassivHaus cases, rather than to compare its calculation method with the detailed simulations.

On the other hand, the ESP-r program is used on all three stages (see figure 2) in order to allow comparisons between results of different stages and because of its flexibility and capabilities to simulate complex passive architecture techniques (such as natural ventilation and energy calculation of solar radiation entering thermal zones).

The first stage of simulation sets the building layout in compliance with Chilean regulation for the 4th climatic zone of Chile and the calculations at this stage aim to identify the minimum energy performance allowed by regulation in that particular climate. Additional model inputs that should be mentioned are the levels of ventilation and infiltration assumed (0.95 ACH and 0.05 ACH respectively), which are based on CIBSE Guide A (2006), and the values assumed for thermal bridges, taken from the Chilean Norm (NCh 853 Of 91, 1991).

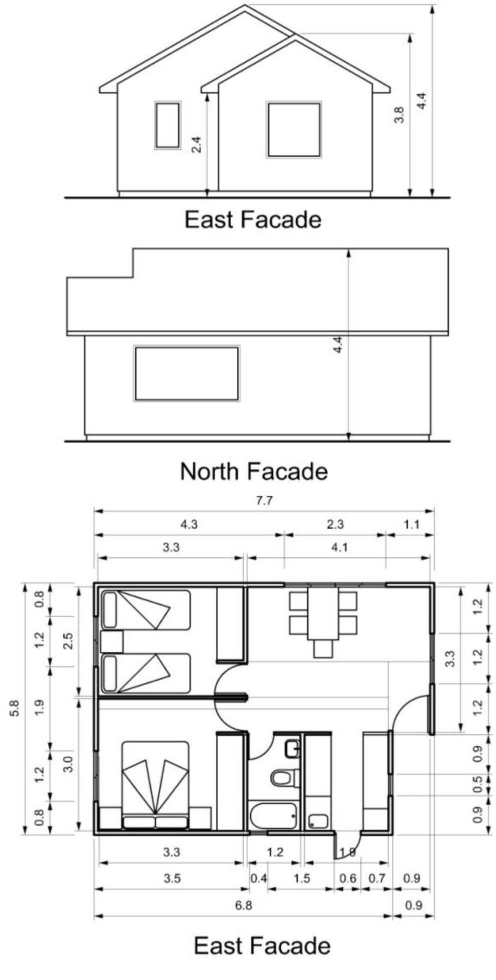


Figure 1: Detached single level Housing layout assessed through energy simulation. Source: Own Elaboration.

Figura 1: Planta de vivienda aislada de un piso evaluada a través de simulación energética. Fuente: Elaboración Propia.

More parameters are considered at this stage of simulations to analyse the effect of reversing the sequence of materials on walls for the typical

Chilean Standards building, where brick walls are commonly insulated (with materials such as expanded polystyrene and plaster) either on the internal or on the external face of the wall. Therefore, two additional case scenarios can be assessed at this stage with the purpose of identifying the importance of internal (or external) thermal mass in the energy performance of buildings that follow the Chilean standards. The potential risk of condensation is not part of this study.

Moreover, the assessed building layout originally shows a window-to-wall ratio of 10%, however, if using the balanced U-Value method stated on the regulation, its window-to-wall ratio can be increased up to the maximum of 19% as the following calculation shows:

- Balanced U-Value for the building assessed – Window-to-Wall Ratio = 10%

$$\frac{\text{Glazing}(7.78\text{m2x}5.8\text{W/m}^2\text{K}) + \text{Door}(2.89\text{m2x}3.48\text{W/m}^2\text{K}) + \text{Walls}(63.5\text{m2x}1.7\text{W /m}^2\text{K})}{\text{Total Facade Area} = 74.17\text{m2}} = 2.2\text{W/(m}^2\text{K)}$$

- Balanced U-Value for the building assessed - Maximum Window-to-Wall Ratio = 19%

$$\frac{\text{Glazing }(14.3\text{m2x}5.8\text{W/m}^2\text{K}) + \text{Door }(2.89\text{m2x}3.48\text{W/m}^2\text{K}) + \text{Walls }(56.9\text{m2x }1.7\text{W/m}^2\text{K})}{\text{Total Facade Area} = 74.17\text{m2}} = 2.56\text{W/(m}^2\text{K)}$$

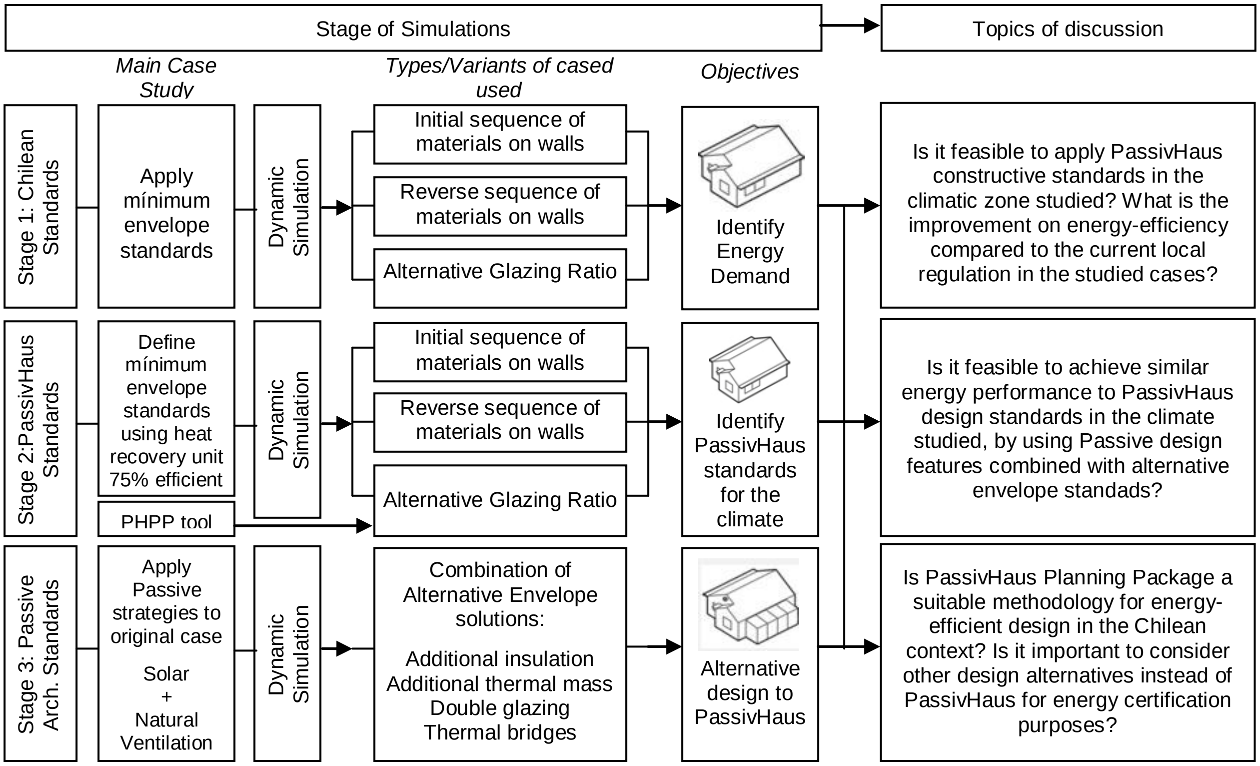
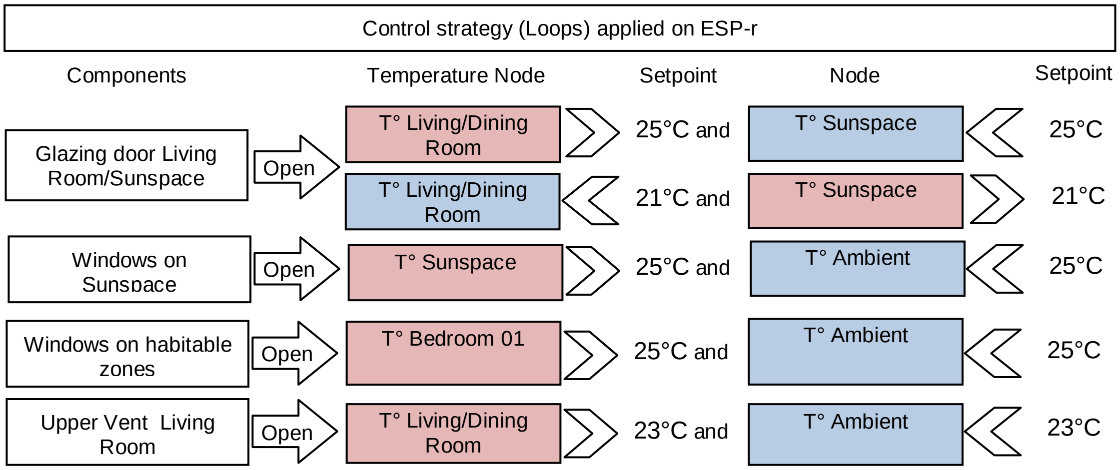


Figure 2: Stages of research and further topics of discussion. Source: Own Elaboration.
Figura 2: Esquema de la investigación y temas de discusión a futuro. Fuente: Elaboración Propia



Control strategy (Loops) applied on ESP-r

Components		Temperature Node	Setpoint	Node	Setpoint
Glazing door Living Room/Sunspace	Open	T° Living/Dining Room	> 25°C and	T° Sunspace	< 25°C
		T° Living/Dining Room	< 21°C and	T° Sunspace	> 21°C
Windows on Sunspace	Open	T° Sunspace	> 25°C and	T° Ambient	< 25°C
Windows on habitable zones	Open	T° Bedroom 01	> 25°C and	T° Ambient	< 25°C
Upper Vent Living Room	Open	T° Living/Dining Room	> 23°C and	T° Ambient	< 23°C

Figure 3: Control strategies applied on ESP-r for the Air Flow Network from stage 3. Source: Own Elaboration.
Figura 3: Estrategias de control aplicadas al modelo de flujo de aire en ESP-r del paso 3. Fuente: Elaboración Propia

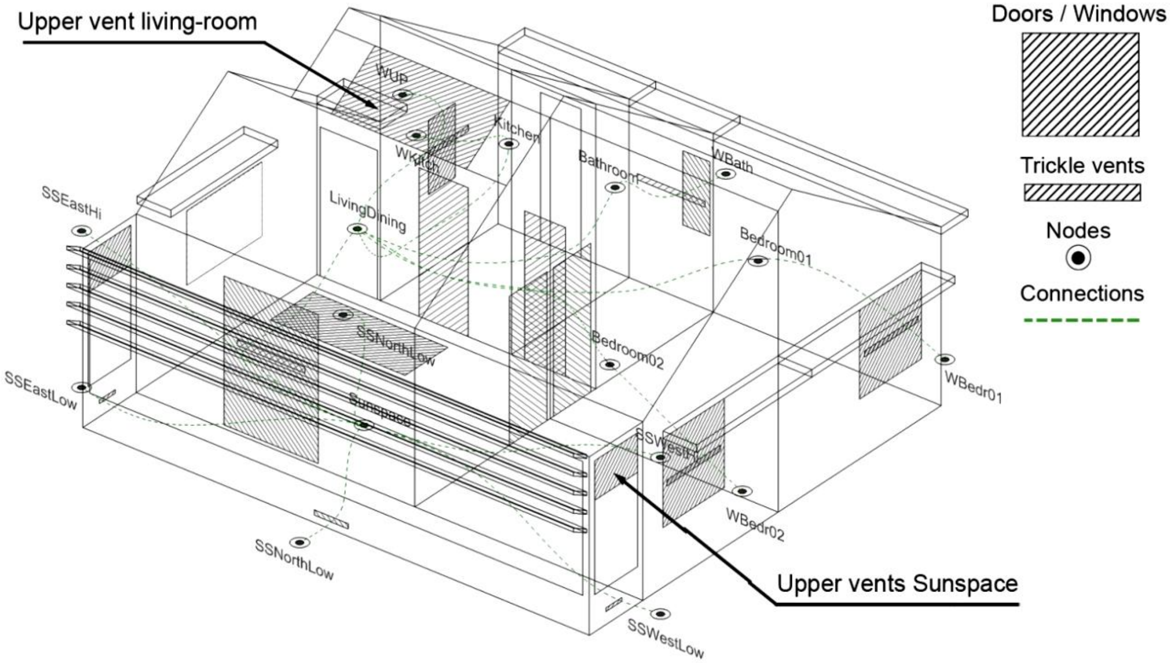


Figure 4: Air flow network components modelled in ESP-r. Source: Own Elaboration.
Figura 4: Componentes del modelo de flujo de aire en ESP-r. Fuente: Elaboración Propia

An additional case scenario with 19% of window-to-wall is included in the study, with the purpose of identifying the differences between the use of the balanced U-Value method and the elemental U-value method of the regulations.

For the second stage of simulations (see figure 2), an upgrade to PassivHaus levels is applied to the building layout. PassivHaus energy performance must not exceed 15 kWh/m^{2}a for heating and cooling requirements, therefore, it is the purpose of this stage to calculate the maximum U-values that must be used to meet this standard for the specific climatic zone of the study. There are several prescribed ways to achieve this and for this study it was assumed to keep two buildings variables as fixed: firstly, a U-value of 1.1W/m^{2}K for all of the building's windows , and secondly, a fixed efficiency of 75% for the Heat Recovery Unit which is the minimum Heat Recovery Unit efficiency allowed by PassivHaus.

For this stage of simulations, thermal bridges are assumed eliminated in accordance with the requirements of the PassivHaus standard.

Finally, a third stage of energy simulations is performed to examine the application of a sunspace (typical passive solar system) combined with a natural ventilation scheme simulated on ESP-r through an Air Flow Network simulation while keeping the rest of the building envelope characteristics the same as for the original case (i.e. same as for the Chilean standards of stage 1). This simulation technique (Hand, 2008) enables to simulate window operation through detailed controlling parameters for the different Air Flow Network components (See figure 3). These control "rules" that were set for the simulations are representing sensitive use of the sunspace in order to gain maximise the heat gains from the sunspace during winter and to control any risk of overheating for all building spaces during summer.

Other air flow components such as trickle vents and building cracks are calibrated in the model to assimilate the uncontrolled heat losses due to ventilation. Figure 4 illustrates the different airflow components modelled in ESP-r to simulate the proposed alternative passive design.

In another case, the simulated passive solar building design is then improved by enhancing the applied U-value standards of the different building components. It is assumed that the current Chilean standards can be improved by simply reducing the thermal transmittance of walls and floors slightly below the maximum values allowed by the standards (e.g. in roofs, the current U-value requirement of 0.38 W/m^{2}K can be easily changed to 0.35 W/m^{2}K, which is equivalent of 100mm Expanded Polystirene insulation). This may represent a highly feasible technical improvement in the current regulation and consequently, a significant energy performance improvement in the building sector.

On the other hand, the relevance of thermal bridges is also investigated by running additional simulations of the same building in which the thermal bridges have been eliminated. The thermal bridge values that are stated in the Chilean Norm are not part of the current mandatory Chilean regulation, however, they are considered as default standards in the current national CCTE.20 Energy Tool that is meant to be used for the Thermal Qualification Procedure.

The purpose of this third stage of simulations is to assess the possible energy benefits in terms of heating and cooling requirements with the use of passive architecture design techniques that may represent an economic and cost-effective alternative against the design methods suggested by PassivHaus standards.

4. Discussion of results

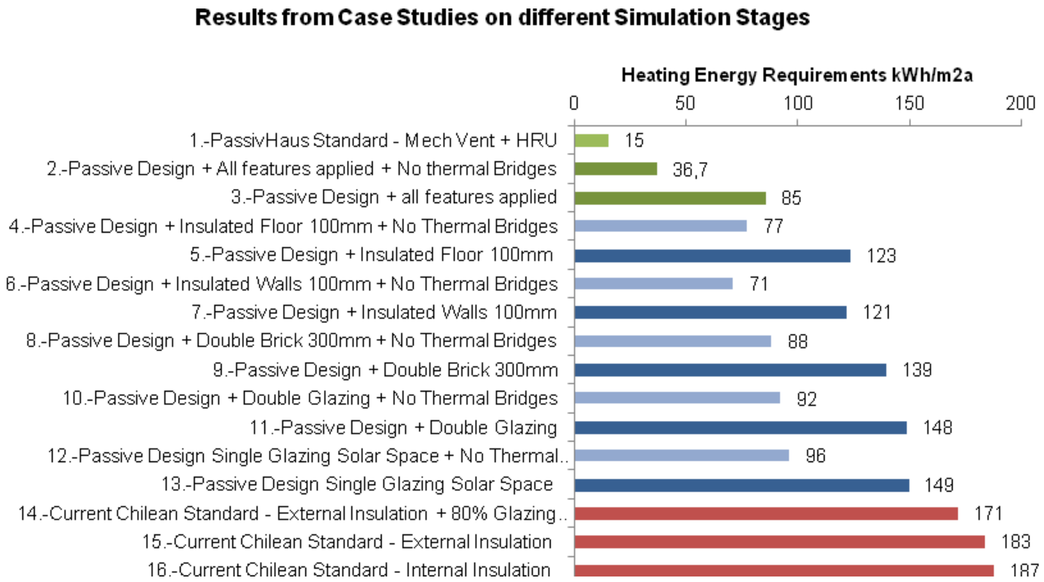
Graphic 1 presents a summary of the main results obtained from the three stages of simulations, whereas a detailed description of the parameters of each simulation is given in Table 4. The cases have been enumerated according to their energy performance rather than stages of simulation.

For the cases of the first stage of the study (case 14, 15 and 16), the results show that the current minimum Chilean standards ensure a maximum heating requirement of approximately 180 KWh/m^{2}a.

In addition, it can be seen that by increasing window-to-wall ratio to the limit allowed by the alternative balanced U-Value method, energy requirements would decrease by about 8% without causing issues of summer overheating (i.e. the cooling load is less than 8 kWh/m^{2}a in these cases). In all cases, an integrated calculation with dynamic energy simulation programs would be an appropriate method for investigating the different options that are allowed by the current Chilean standards for energy compliance purposes.

Case 15 presents a slight improvement on energy performance in comparison to case 16, which provides energy savings of less than 3% (this is approximately CLP$20.000 annual savings from heating for the building of this study). However, this illustrates that from the passive design point of view, it is preferable to consider the use of internal thermal mass in the specific climate in order to store solar heat gains and reduce the energy demand. It could be suggested that if the future Chilean regulations will continue to provide prescribed design guidelines, such as for example glazing ratios and maximum U-values, it would be feasible to also recommend optimal levels of thermal mass for each climatic zone. Dynamic energy simulation could be a helpful tool for such a purpose.

For the second stage of simulations it was assumed that due to the early stage of development of highly efficient heat recovery equipment in Chile the minimum requirement of 75% efficiency constituted an acceptable fixed



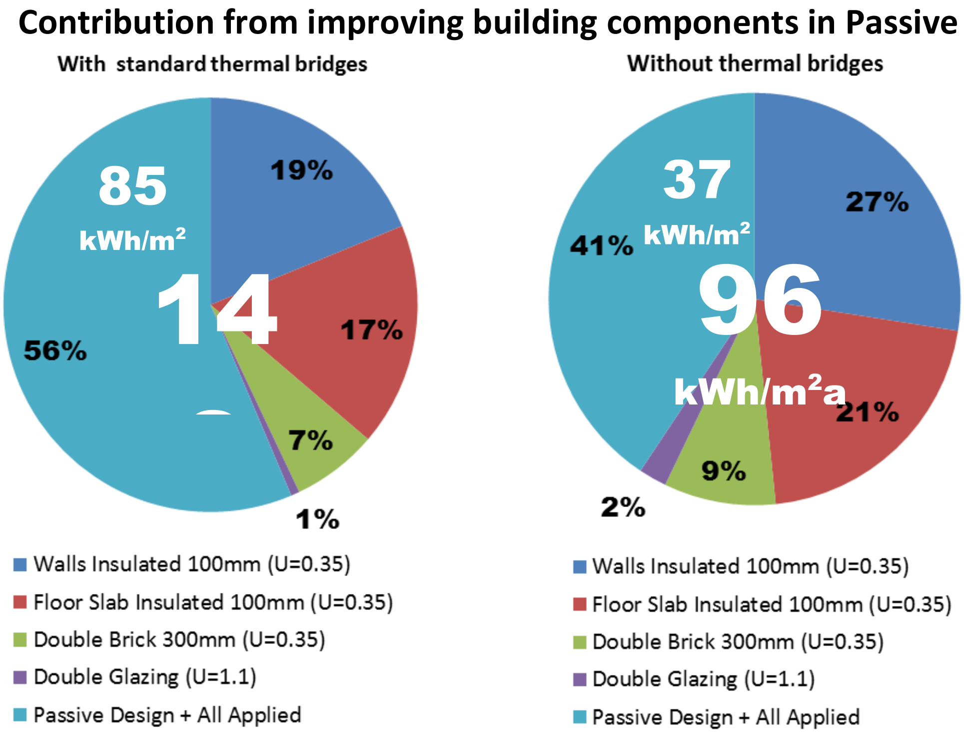
Graphic 1: Results from Case Studies for the different Simulation Stages. Source: Own Elaboration.
Grafico 1: Resultados para los casos de estudio en las diferentes etapas de simulación. Fuente: Elaboración Propia

Table 4: Description of the simulated cases. Source: Own Elaboration.
Tabla 4: Descripción de los casos simulados. Fuente: Elaboración Propia.

CASE	DESCRIPTION
1.-PassivHaus Standard - Mech Vent & HRU	Mechanical Ventilation + 75% efficient Heat Recovery Unit Envelope U-Values: Wall, roof and floor: 0.24W/m2K Glazing U-Value:1.1W/m2K Ventilation: Average Air flow Rate:120 m^3/h - 0.95 ACH Air leakage level: 0.6 ACH @ 50Pa – near to 0.001 ACH at normal pressure conditions. internal heat gains: 2.1 W/m2 No thermal bridges
2.-Passive Design + All features applied + No thermal Bridges	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall, roof and floor: 0.35W/m2K Glazing U-value: 1.1W/m2K Windows increased 80% in north, east and west facades No thermal bridges
3.-Passive Design + all features applied	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall, roof and floor: 0.35W/m2K Glazing U-value: 1.1W/m2K Windows increased 80% in north, east and west facades Thermal bridges: According to linear thermal transmittances NCH 853Of91
4.-Passive Design + Insulated Floor 100mm + No Thermal Bridges	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: 0.35 W/m2K Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades No thermal bridges
5.-Passive Design + Insulated Floor 100mm	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: 0.35 W/m2K Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades Thermal bridges: According to linear thermal transmittances NCH 853Of91

6.-Passive Design + Insulated Walls 100mm + No Thermal Bridges	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 0.35W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades No thermal bridges
7.-Passive Design + Insulated Walls 100mm	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 0.35W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades Thermal bridges: According to linear thermal transmittances NCH 853Of91
8.-Passive Design + Double Brick 300mm + No Thermal Bridges.	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 0.345W/m2K (additional thermal mass)- Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades No thermal bridges
9.-Passive Design + Double Brick 300mm	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 0.345W/m2K (additional thermal mass)- Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades Thermal bridges: According to linear thermal transmittances NCH 853Of91
10.-Passive Design + Double Glazing + No Thermal Bridges	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 1.1W/m2K Windows increased 80% in north, east and west facades No thermal bridges
11.-Passive Design + Double Glazing	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 1.1W/m2K Windows increased 80% in north, east and west facades Thermal bridges: According to linear thermal transmittances NCH 853Of91
12.-Passive Design Single Glazing Sunspace + No Thermal Bridges	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades T No thermal bridges
13.-Passive Design Single Glazing Sunspace	7.7m2 Single-glazing sunspace Natural ventilation - Average Airflow rate: 145.5 m^3/h – near to 0.95 ACH on winter period Envelope U-Values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades Thermal bridges: According to linear thermal transmittances NCH 853Of91
14.-Current Chilean Standard - External Insulation + 80% Glazing Increased	Ventilation - Average Airflow rate: 120m^3/h – near to 0.95 ACH Infiltration: 30 m^3/m^2*h @ 50Pa – near to 0.5 ACH Envelope U-Values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Windows increased 80% in north, east and west facades Insulation on external face of walls Thermal bridges: According to linear thermal transmittances NCH 853Of91

15.-Current Chilean Standard - External Insulation	Ventilation - Average Airflow rate: 120m^3/h – near to 0.95 ACH Infiltration: 30 m^3/m^2*h @ 50Pa – near to 0.5 ACH Envelope U-Values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Insulation on external face of walls Thermal bridges: According to linear thermal transmittances NCH 853Of91
16.-Current Chilean Standard - Internal Insulation	Ventilation - Average Airflow rate: 120m^3/h – near to 0.95 ACH Infiltration: 30 m^3/m^2*h @ 50Pa – near to 0.5 ACH Envelope U-Values: Wall: 1.7W/m2K - Roof: 0.35 W/m2K - Floor: Concrete Slab Uninsulated Glazing U-value: 5.8W/m2K Insulation on internal face of walls Thermal bridges: According to linear thermal transmittances NCH 853Of91



Graphic 2: Contribution from improving building components in passive design (with standard thermal bridges and without thermal bridges). Source: Own Elaboration.

Grafico 2: Contribución de mejoras en la envolvente en el diseño pasivo (con puentes térmicos estándar y sin puentes térmicos. Fuente: Elaboración Propia

assumption for the analysis. In addition, a minimum standard for glazing properties was established by using the PHPP tool in a way that wall and roof thicknesses remained within reasonably affordable levels. The resultant U-value of the window that was used was 1.1W/m^{2}K and the solar transmittance (g-Value) was 0.56.

The results obtained using the PHPP calculation tool show that in order to meet the PassivHaus certification target (i.e.15kWh/m^{2}a for heating and cooling requirements) the U-values for roof, floor and walls had to be 0.11W/m^{2}K.

However, ESP-r results for the same building case show that PassivHaus certification is achievable with even lower construction standards than those estimated by the PHPP tool, i.e. a U-value of 0.24W/m^{2}K on all opaque components is satisfactory for meeting the PassivHaus target (case 1 in Table 4). These results demonstrate an interesting opportunity to introduce the PassivHaus building concept into milder climates such as the one for this study by using considerably lower insulation levels than those required to meet the PassivHaus target for the colder climates of Northern Europe.

The third stage of simulations (cases 2 to 13 in Table 4) revise energy performance improvements through the application of passive design solutions as an alternative to PassivHaus standards. Results show that implementing a single-glazing sunspace in the north facade of 7.7m^2 to the building can contribute to an energy saving of 22 to 34 kWh/m^{2}a compared with the base cases of the current Chilean building standards (these energy savings are equivalent to annual savings of approximately CLP$118800 to CLP$183300). On the other hand, if construction practices improve in a way that the thermal bridges of the building are eliminated (case 12 against case 13 in Table 4) the energy requirements for heating purposes are reduced by approximately 35% (thermal bridges account for approximately 53 kWh/m^{2}a out of the total heat losses in the base case).

The simulation results for the different upgrades on the building components are summarised in Graphic 2, the percentages in the chart should be considered only concerning the case study and its scale. However, these percentages illustrate the importance of improving the thermal envelope and energy performance of housing of similar characteristics through passive design strategies.

With regards to the improvements of building envelope components, it is found that the best choices in terms of energy savings are to increase the insulation levels on walls or beneath the floor slab. In particular, it is found that including insulation below the floor slab is an important design recommendation when taking into consideration that the current Chilean regulation does not require any mandatory insulation layers on floor components that are in contact with the ground, and that it is not possible to improve this part of the building after the construction stage.

Moreover, it can be observed from the results that the alternative proposed building standards combined with passive solar strategies represent a feasible alternative to PassivHaus standards (see Graphic 1, cases 2 and 3). Implementing all of the passive design strategies that were investigated in this study would result in a reduction of heating requirements of the studied case, of approximately 53% compared with those required by the current Chilean standard (see Graphic 1, cases 15 and 16).

On the other hand, PassivHaus standards applied to the case study, represent a reduction of energy consumption of around 92% in comparison to Chilean standards. This high-efficiency performance is clearly due to the reduction of heat losses caused by integrating a mechanical ventilation system with the heat recovery unit. This key feature of the PassivHaus configuration may also be applicable to alternative building standards such as the ones studied in cases 2 and 3, taking in consideration that these building standards represent more affordable envelope solutions than PassivHaus envelope requirements.

Conclusions

Energy efficiency opportunities from passive design strategies were demonstrated by using detailed simulation tools such as ESP-r and it was shown that such tools could offer additional opportunities for low energy building designs if they are allowed to be introduced as methods of building energy certification.

It has been also highlighted that the current technical aspects of regulation should be enhanced in the future, as exemplified by other regulations and Standards such as the Passivhaus standard, in a way that could guide professionals on considering important aspects of energy efficiency, for example the air leakage and the avoidance of thermal bridges.

Dynamic simulation results using ESP-r suggest that Passivhaus energy performance can be achieved with more affordable construction standards than those prescribed by the PassivHaus tool (PPPT). The ESP-r output shows that applying opaque U-values of 0.24 W/m^{2}K was enough to meet the PassivHaus target of 15 kWh/m^{2}a for space heating and cooling. This suggests that PassivHaus standards could be implemented on the climate in a less restrictive and more economic way than that prescribed by the PassivHaus tool.

Cases of passive solar designs that incorporate natural ventilation were also analysed as an alternative to the prescribed PassivHaus standards in order to quantify the potential of such passive design techniques in reducing energy requirements. The passive design was studied in combination with better envelope standards than those currently prescribed by Chilean regulations. From the results of the simulations it was concluded that passive design could also significantly reduce the heating energy requirements of the building (controlling cooling demands by effective natural ventilation) and it constitutes a feasible alternative to PassivHaus standards option for the climate of the study.

The passive design approach should not be omitted by the future regulations of Chile since passive design strategies can be cost-effective and have lower costs of maintenance than the PassivHaus active approach. However, passive solar systems such as the one studied (attached sunspace for passive heating) may require significant levels of control that may compromise their acceptance by the local public and conversely their energy performance when implemented in buildings. Therefore, it is found important to assess passive design through dynamic simulation tools, in order to study in detail its energy performance and operation required.

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