Methods and New Results for Design Recommendations on Sustainable Solar and Passive Housing in Emerging Countries and in Mediterranean Climate Zones

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Abstract

Emerging countries like Chile in Latin America with their rapidly growing economy and energy use in the housing sector present new challenges for ecological and social sustainability. Sustainable passive and solar housing, including passive cooling and passive solar heating here, is a promising strategy to improve thermal comfort in the Mediterranean climate of Central Chile with its hot and dry summers and cool, but sunny winters.

The investigation applied a strategy of using advanced methods of research in order to develop simple and flexible concepts and tools for the design of solar and passive houses, which are extendable to similar climate zones of Latin America and emerging countries in other regions.

The evaluation of thermal building behavior is based on extensive parametric studies, both for a reference room and for complete passive houses. The thermal simulations were realized with a test year for Central Chile and hourly climate data, prepared with an own methodology.

The systematic design recommendations for simple and advanced solar and passive houses show that with an optimized design and thermal management of houses, it's possible to improve significantly the thermal comfort conditions in economically accessible dwellings of the region.

Latest results of the author's participation in international scientific cooperation in Europe and Latin America and the research for his advanced PhD-thesis are presented as a contribution to sustainable building.

Keywords: solar architecture, passive design, thermal comfort, thermal simulation, sustainable building

1. Introduction

Emerging countries like Chile with their rapidly growing economy and energy use in the housing sector present new challenges for ecological and social sustainability. Sustainable passive and solar housing, including passive cooling and passive solar heating here, is a promising strategy to improve thermal comfort in the Mediterranean climate of Central Chile with its hot and dry summers and cool, but sunny winters. This type of climate presents a challenge because overheating and cold both present serious problems in dwellings. On the other side, it offers interesting potentials as well, because - different from very cold septentrional or warm-humid tropical climate regions - thermal problems can be managed to a large extent with passive strategies, as will be shown below. Although rarely mentioned explicitly, earthquake resistance of designs was always considered as a condition in a seismic country like Chile. Sustainability in an emerging economy requires that building materials and elements should be regionally producible in the long run and maintenance viable with local resources.

Until the 1990s there was only a small number or publications from Chile available on the improvement of thermal comfort and energetic efficiency in dwellings with limitations in their climatic and constructive scope or methodology and without access to thermal simulations or large-scale measurements. According to urgent necessities, many authors concentrated on small improvements of thermal insulation on critical building elements like (Rodriguez et.al. 1990), (Campos 1994) or (Sarmiento 1995). The last source adds some simple information on passive solar systems and climate data. Other studies like (Román 1991) were scientifically detailed, but refer to special or extreme climate conditions as in the high Andes. In the present millennium, some new efforts have been published to improve dwellings in Chile, that have concentrated on the thermal and

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energetic improvement of dwellings in the near future, without putting emphasis on the final aim of houses with full passive climatization and the respective constructive requirements in the mediterranean climate of Central Chile or another important Chilean climate zone. Publications typically refer to special projects or small, but more realistic thermal improvements in the near future for all Chilean climate zones from the desert north, dry and cold Andes in the east, the meditarreanean center to the cold and humid or even subpolar south as described in (NCh 1079-2008) and (Peel et. al. 2007). In his PhD, (Bustamante 2001) elaborated a residence climate zoning methodology and proposals for the thermal improvement of dwellings for Chile as a whole, based on thermal simulations with daily profiles from monthly mean values and aimed at the reduction of (calculated) energy consumption for heating. The PLEA conference 2003 took place in Santiago and counted with some interesting Chilean publications: for example, (Fissore 2003) from Concepción in southern Chile avoids thermal simulations as too onerous for small projects and determines cost efficient insulation levels with a simplified computer model. (Trebilcock 2003) analyses simple options to improve energy efficiency in 3 low cost housing examples in 3 different Chilean climate zones. Due to the lack of hourly climatic data for simulation, her climate data for simulation were based on "synoptic data plus maximum and minimum". In (Bustamante 2009a) and (Bustamante 2009b), Bustamante makes proposals for the improvement of energy efficiency in low cost housing in different Chilean climate zones.

Corresponding to what was and is already available from Chile, this investigation uses a different approach and can use hourly climate date for a complete test year for the most populated and important climate zone of Chile. In its final proposals, it takes into account the typical restrictions of time and resources for design and thermal or energetic optimization. Accordingly, the investigation was based on the strategy of applying advanced methods of research in order to develop simple and flexible concepts and tools for the design of solar and passive houses, which can later be effectively adapted to their implementation under varying conditions in different regions with comparable conditions and restrictions.

In this study, sustainable passive and solar housing, including passive cooling and passive solar heating, means that no non-renewable energy is used for thermal purposes neither complicate active solar systems; only mechanical use of electric energy for simple ventilation systems is considered in some cases. Motorized or even computerized systems for thermal management are avoided to prevent problems with cost and maintenance in a region where they are not common in dwellings or private houses.

2. Methodology

The evaluation of thermal building behavior is based on extensive parametric studies, both for a reference room and for complete "passive" houses. The thermal simulations were realized with a test year for Central Chile with hourly climate data, prepared with an own methodology, that was published by the author of this paper in (Müller 2001). The original hourly climate data for Santiago were obtained thanks to the cooperation of the National Centre for the Environment CENMA from measurements of the National Environmental Commission CONAMA, both in Santiago de Chile; the mean reference values that oriented their combination came from (Dirección Meteorológica de Chile 1991) and (Sarmiento 1995). The climate of the central region of Chile can be characterized as mediterranean according to (NCh 1079-2008), (Peel et. al. 2007) and (Instituto Nacional de Estadísticas 2000). It's challenging because it combines thermal problems in summer (high maximum temperature and solar radiation) and winter (low temperatures) with a promising potential for passive climatization, thanks especially to its low night temperatures in summer and high levels of solar radiation in winter.

The evaluation of thermal building behavior is now based on an increased number of simulations for extensive parametric studies with the thermal simulation program Derob-LTH, which could be used thanks to the cooperation with Lund University (Sweden), both for a reference room (now >1000 cases) and for complete (passive) houses (>100 houses). Therefore, the investigation and publication can consider and present an extended range of building elements, passive climatization strategies and building parameters in comparison to previous versions.

Thermal simulations with DEROB-LTH permit the hourly determination of interior operative temperatures θ_o, defined as the mean value of indoor air temperature and the indoor surface temperatures weighted by their respective areas. Internal heat gains from a "typical" residential use are considered in all simulations. From the simulation results, mean daily degree-hours of heat Gh26o and mean daily degree-hours of cold Gh19o could be calculated in (Kh/d) for each period of N hours with especially written own software according to the following definition:

$$\mathrm{Gh}_{\mathrm{base}} = \left\{ \sum_{i=1}^{N} (\theta_o - \theta_{\mathrm{base}}) \times 1\mathrm{h} \right\} \times 24 / \mathrm{N} \quad (\mathrm{Kh/d}) \qquad \text{(eq. 1)}$$

The index of Gh26o and Gh19o indicates the base temperature θ_{base} and the use of operative temperatures and in this publication values for the hot period (December - February) and cold period (May - September) were calculated and analyzed.

Parallel to the thermal simulations, classic building code calculations were adapted and applied: simple building characteristics were calculated in a spreadsheet according to (German versions of) ISO or European building codes ((E DIN EN ISO 13790, 1999) and related ones), which are similar to, but more complete than local Chilean codes; basic characteristics of local building materials were taken from Chilean code (NCh 853.Of91) when available; necessary characteristic values and correction factors in building codes were determined with special thermal simulations; special simple models for passive design aspects that are not considered in building codes, e.g. night ventilation, were established. This way, the calculation methods originally created for the description of thermal behavior in winter and the determination of energy needs, were adapted for the new climate zone and extended to determine basic thermal parameters for passive and solar houses with free-floating temperatures in the cold and hot period. An earlier version of crucial building parameters had been published with more details by the author of this paper in (Müller 2006).

The three crucial building parameters, which can be defined both in the cold and hot period based on the adapted calculation methods, are size independent:

- gains-to-loss ratio GL (dimensionless)
GL describes the relative size of heat gains compared to heat losses in the climate zone (at the selected comfort level θ_{base});
- time constant τ (tau) (h)
τ describes how fast a building reacts to varying thermal influences and how long it is able to compensate them;
- utilization factor η (eta) (dimensionless)
η describes how efficient a building is making use of passive and internal heat gains (at the selected comfort level θ_{base}) and depends on thermal capacity, heat gains and heat loss coefficient.

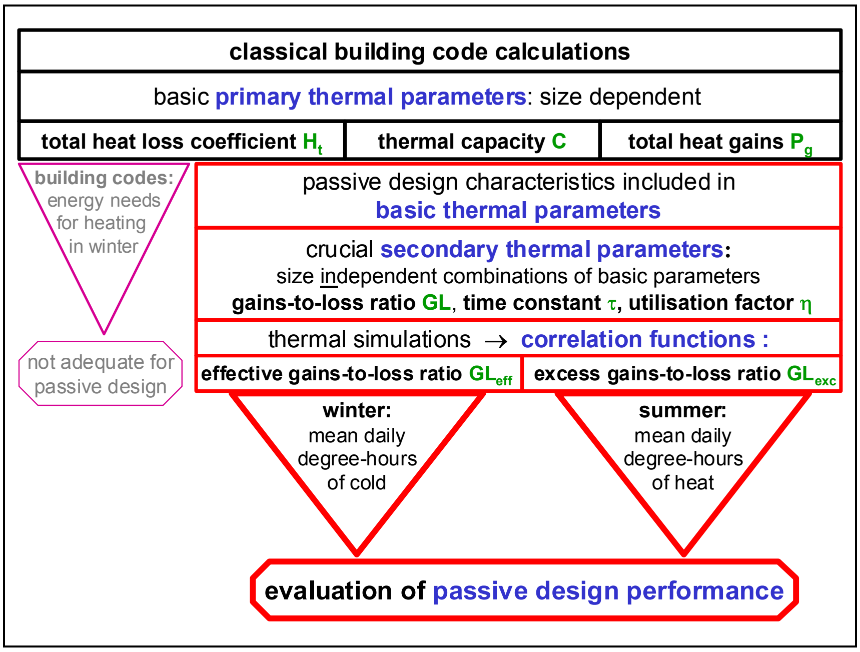

Fig. 1: Concept for the development of crucial building parameters and design recommendations

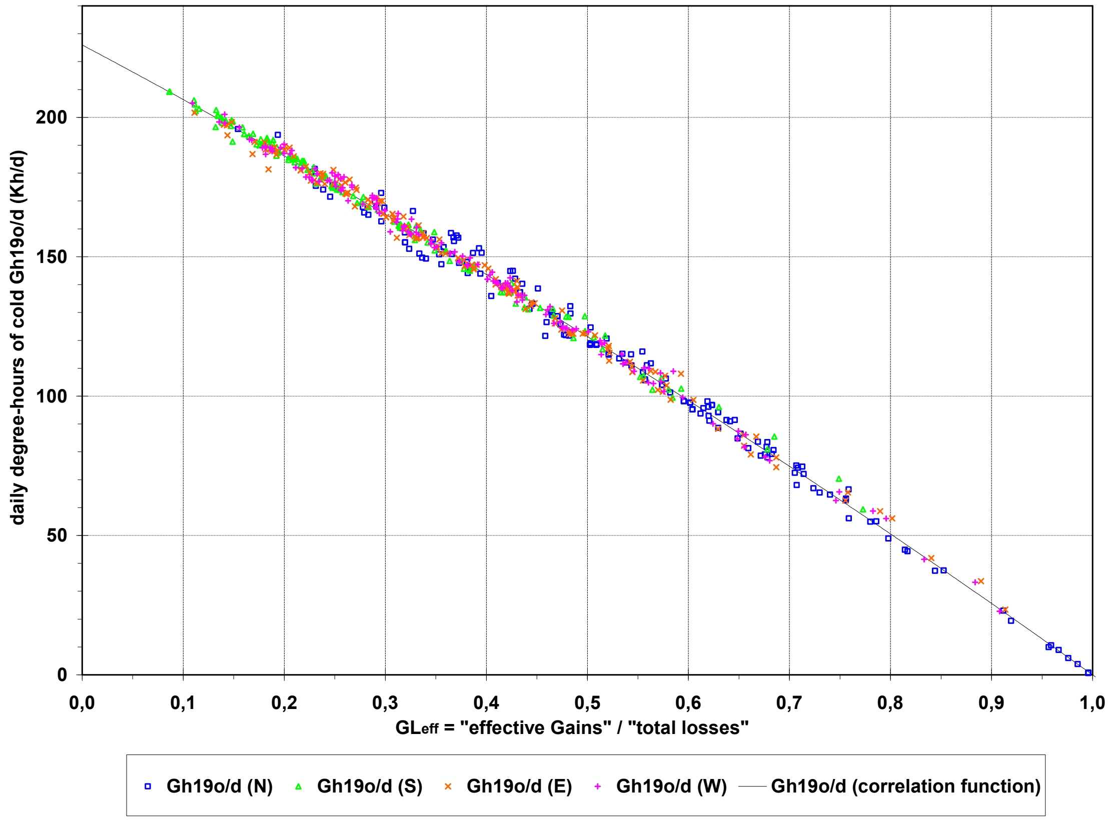

Fig. 2: Correlation for winter (May - September), indicating main orientation N-S-E-W

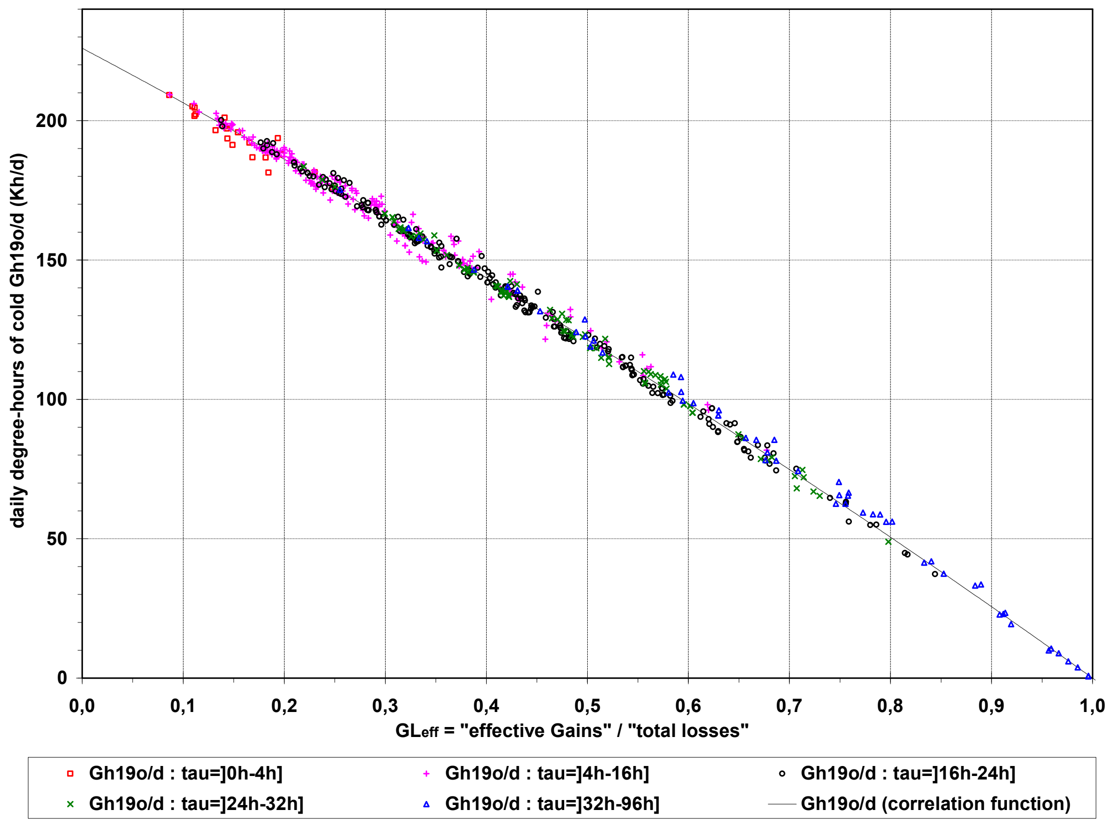

Fig.3: Correlation for winter (May - September), indicating range of time constant τ (tau)

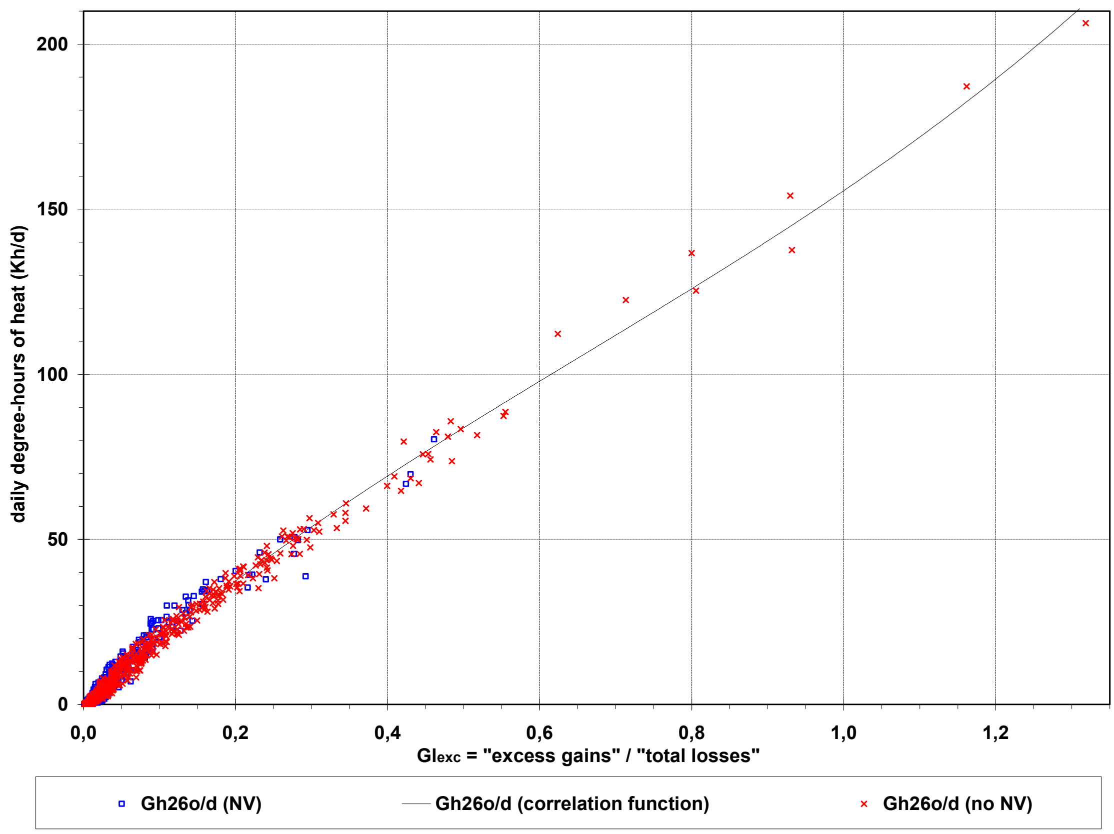

Fig. 4: Correlation for summer (December - February), indicating night ventilation NV

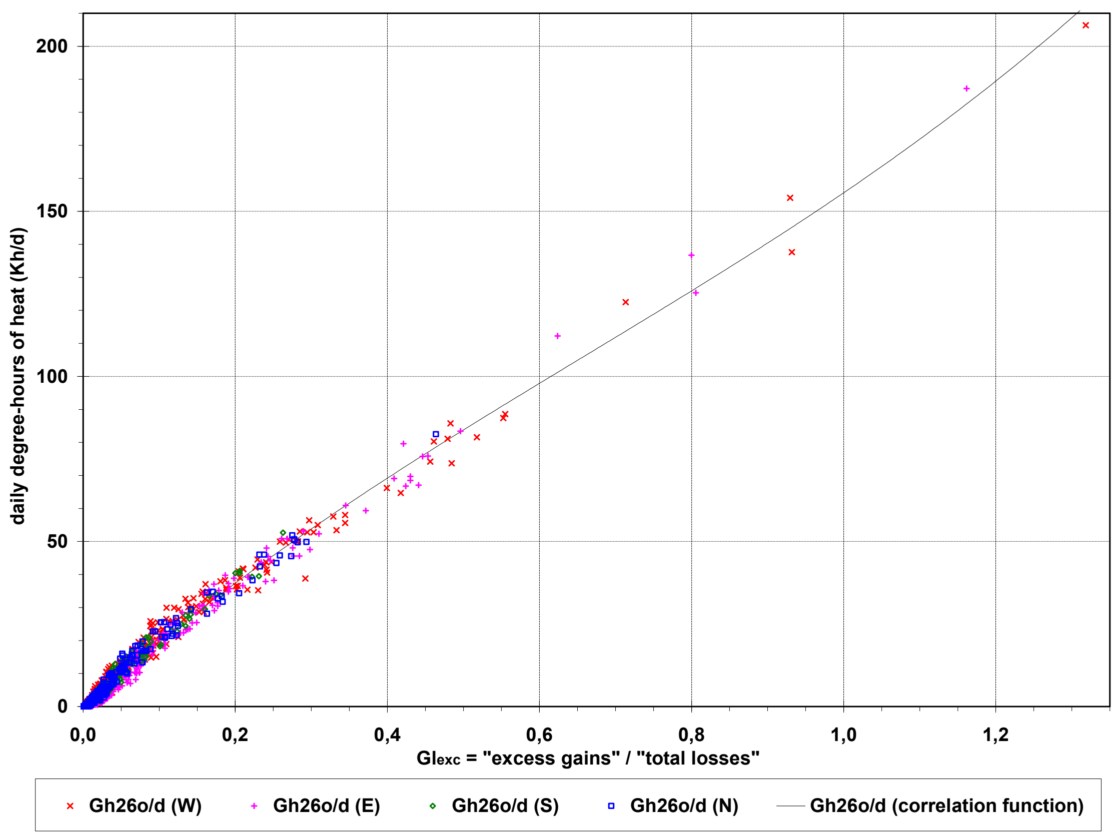

Fig. 5: Correlation for summer (December - February), indicating main orientation N-S-E-W

The adapted calculation methods and crucial building parameters were developed and verified with the thermal simulations to permit good correlation with just a minimum of free parameters determined as part of the process. This process is summarized in figure 1, the results are presented in figures 2 and 3 for the cold period, “winter”, and in figures 4 and 5 for the hot period, “summer”.

Each data point in figures 2 to 5 represents a different reference room considering its construction and thermal management (shading and ventilation). The correlation functions for the hot and cold period connect the building code calculations for each case with its resulting comfort conditions determined from simulation. The simulations here intentionally cover an increased and very wide range from extremely heavy thermal problems resulting from inappropriate traditional and modern designs to (almost) perfect comfort conditions in solar and passive design proposals. The symmetric scattering of data points both above and below the correlation curves confirms that there is not systematic bias according to the marked parameter. The correlation is for all data points combined; their distinctive markings in these example figures permit the separate analysis of different parameters for – positive or negative – design recommendations..

3. Results

3.1. Simulations with the reference room

Design recommendations can be derived and formulated corresponding to the intended target group and purpose:

For building physicists, engineers and other mathematically oriented professionals, important design aspects can be derived in terms of the crucial building parameters, from the correlation graphs with indicated parameters and their analysis according to their dependencies:

- The cold period in figures 2 and 3 requires a considerable constructive effort with maximized solar heat gains, a sufficient amount of thermal mass (combined with external thermal insulation) for a very large time constant τ and minimized heat losses as is shown by the small, but available number of cases on the right side of figures 2 and 3 with high GLeff values close to the maximum value of 1 and presenting only minimal thermal problems in winter. Very low time constants and wrong orientation, especially south / away from the sun, are the source of the largest thermal problems; only correct solar orientation to the north with a maximum time constant permits effective use of solar energy and thus a passive solution for thermal comfort in this season.
- The hot period in figures 4 and 5 is easier to resolve with an adequate design, although there exist many cases in theory (and reality) with unnecessary and large or extreme thermal problems (typical of “modern” and low cost dwellings), because of the wrong orientation to the east or west combined with deficient solar protection and no or inefficient night ventilation. Even without night ventilation (sometimes complicate in urban regions), it’s possible to minimize thermal problems with minimized solar heat gains, a reasonable amount of thermal mass to compensate for daily temperature variations and minimized solar heat gains through windows and the roof/ceiling (cf. figure 7 and its analysis below) as is shown by the considerable number of cases with very low GLexc in figures 4 and 5 offering good to perfect thermal comfort conditions in the hot season.

Together, these 4 figures offer a first proof that passive design is possible in this climate region; its efficiency is predicted correctly by modified classical building code calculations and verified by hourly dynamical thermal simulations for the reference rooms here.

Accordingly, design recommendations can be resumed in terms of the two most condensed crucial building parameters when you are conscious of their dependencies:

- The "effective-gains-to-loss ratio" GLeff for the cold period (“winter”) describes the relative size of heat gains that are useful for thermal comfort, compared to thermal losses (at the selected minimum comfort level of 19°C) - GLeff should be as close as possible to 1.
- The "excess-gains-to-loss ratio" GLexc for the hot period (“summer”) describes the relative size of heat gains that are harmful to thermal comfort, compared to thermal losses (at the selected maximum comfort level of 26°C) - GLexc should be as low as possible.

For the initial design stage, architects and other professionals with a more graphical or practical focus, design recommendations can be derived directly from the simulation results for the reference rooms without referring to the modified building code calculations. They are shown and formulated directly for the different aspects of thermal design:

Figure 6 gives a first example of this approach, showing the combined effect of different basic construction types on comfort conditions in the reference room in the hot and cold period according to the four main orientations of windows on the main façade: Each data point represents a mean value for different, but corresponding designs with window types, insulation, shading and ventilation levels corresponding to the basic house type. Optimized solar orientation (north in the southern hemisphere here) is crucial for reducing overheating in summer and maximizing solar gains in winter; southern orientation lacks solar gains in winter, being uncritical in summer, east and west orientations present heavy overheating problems in summer without sufficient solar gains in winter; the heavier rammed earth houses with their increased thermal capacity in comparison to wood panel houses permit better use of solar gains in winter and reduce overheating in summer. The correctly north oriented solar house proposals with even better thermal insulation including high quality windows and optimized ventilation strategies, improved solar gains respective shading prove what can be obtained with simple but carefully optimized solar design in this climate zone: thermal problems both in summer and winter are widely resolved.

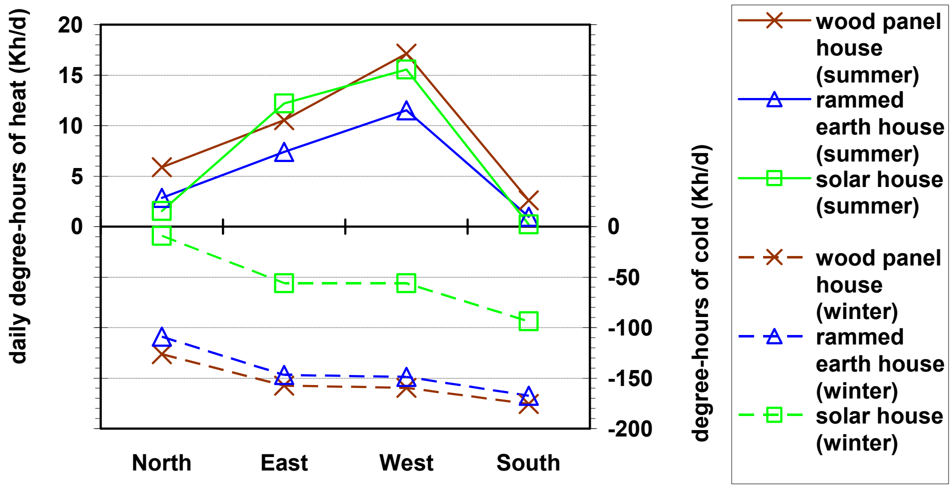

Fig. 6: Analysis of orientation for different house types for daily degree-hours of heat and cold of operative temperatures; for summer (December – February, base 26°C, >0) and winter (May – September, base 19°C, <0) in Santiago (Chile)

As a second example, the following figure 7 analyzes priorities for thermal insulation, depending on thermal mass and construction type: the most striking result is the importance of roof insulation in summer, but not so on other surfaces. It can be understood from the low latitude of -33.6° that results in an almost vertical and therefore high incidence of solar radiation on roofs in summer in Santiago. Thermal capacity increases from wood panel houses, passing through brick constructions and reaches its maximum in rammed earth houses, improving thermal comfort in summer accordingly. In winter, thermal comfort improves gradually with improved insulation as you would expect, but only passive houses with maximized solar gains and maximum thermal capacity (from thick rammed earth walls, “tapial” in Spanish) combined with lowest heat losses offer the best results.

Some additional examples of this type of presentation and analysis, although based only on the hottest (January) and coldest month (July) of the year, can be found from the author in (Müller 2007; in Portuguese) and in his Spanish manual (Müller 2002) together with traditional design methods, more detailed descriptions and recommendations. The complete set and final systematic design recommendations will be part of the PhD thesis itself in the near future.

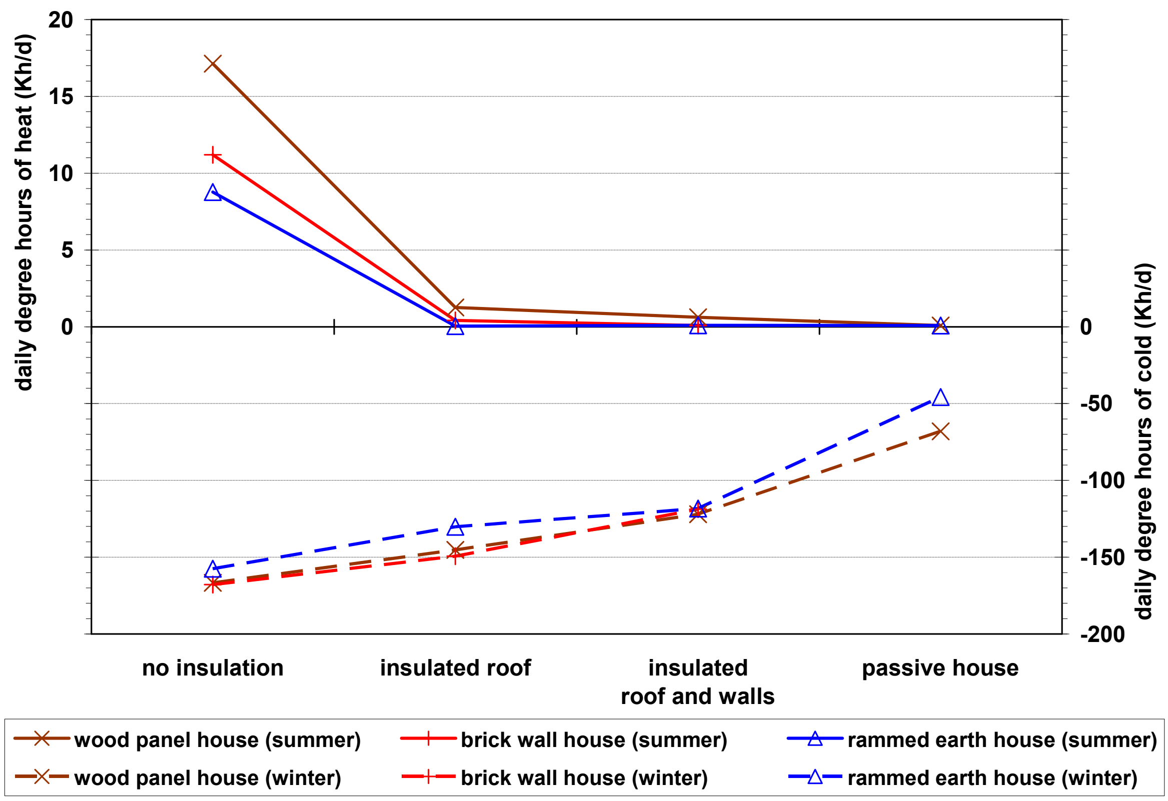

Fig. 7: Analysis of priorities for thermal insulation depending on thermal mass and construction type for summer (December – February, base 26°C, >0) and winter (May – September, base 19°C, <0) in Santiago (Chile)

3.2. Simulations and comparison of complete houses

A second series of hourly thermal simulations was realized and analyzed with the same tools for complete houses with a more complex geometry but a reduced parameter range, considering just the most interesting and logical combinations ranging from conventional, "normal" or "standard" designs to passive design proposals.

Figures 8, 9 and 10 show different examples of simulated houses without roof surface, so that the interior distribution of rooms and windows on the opposite side of the house are equally visible. The graphs were generated with the thermal simulation program itself and show its geometric model for the latitude, date and hour indicated in the graph (15th of July, 14:00 true solar time if not indicated differently), seen from the sun's position, so that solar incidence and shading can be judged directly. The yellow surfaces represent external shading surfaces of the model, in the case of vertical shading surfaces they represent the shading effect of very thick walls made of rammed earth (at least 43cm thick depending on insulation with the windows in the center); windows are blue, walls and floor seen from inside/outside are orange/red. The simulation results presented in figure 11 are for the living room - the big center one - and the bedroom in front seen on the right side; both have windows on the same main façade with its orientation as indicated for the house.

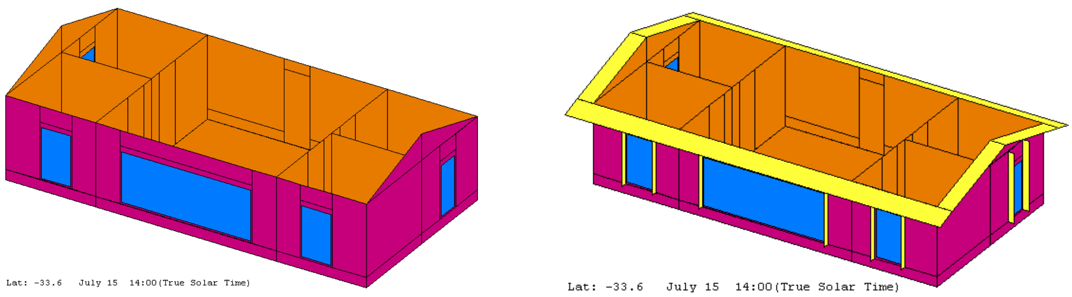

Fig. 8: Normal house without shading devices and thin walls (left); standard rammed earth house with shading (right) (shown without roof, front: north side; 15.7. 14:00 true solar time, seen from the solar position)

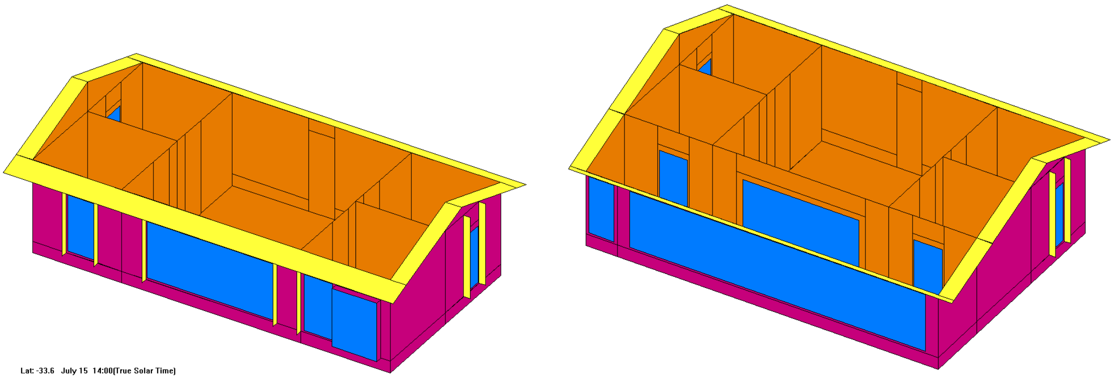

Fig. 9: Passive houses, rammed earth: with Trombe wall on right side (left graph); with winter garden in front (right graph) (shown without roof, front: north side; 15.7. 14:00 true solar time, seen from the solar position)

Figure 10 shows the same passive house, made of rammed earth and optimized for direct solar gain in winter: The two graphs verify and demonstrate that geometric calculations for overhang size and position are correct, so that the solar gain – window is fully exposed to the sun on the design day in the coldest month of July (left graph) and fully shaded in the design day for in the hottest month of January (right graph). It can be observed that fixed shading for the west (and east) façade is not feasible, but obviously the passive houses here have additional mobile shading applied in summer for all windows (simulated, but not shown in the geometric model).

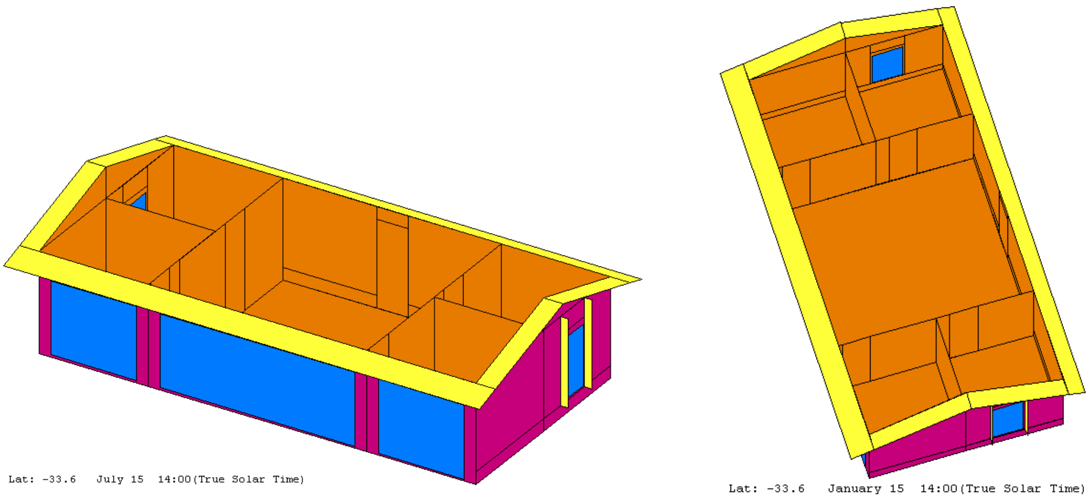

Fig. 10: Passive house, rammed earth, optimized for direct solar gain winter (left graph) and in summer (right graph) (shown without roof, front: north side; representing coldest month on 15.7. and hottest month on 15.1.; 14:00 true solar time)

The following analysis refers to the houses shown above and their short descriptions in figure 11, showing their simulated thermal behavior depending on thermal design and management. They are grouped according to basic wall construction (separated by green lines for easier reading of the graph) and sorted approximately with step by step thermal improvements from left to right. The main parameter variations are:

- construction type: light walls (hollow wood panels), 140mm of brick, 400mm of rammed earth with normal or low density (for reduced heat loss) with corresponding plaster;
- level of exterior insulation on walls (when indicated in the title) with corresponding roof insulation; varying window orientation, size and quality (simple, double, double low emissivity glazing);
- different passive heating strategies in corresponding cases: in summer night ventilation; in winter Trombe walls in the northern bedrooms, winter garden on the north façade (see figure 9), increased direct solar gains with large or maximized windows to the north (see figure 10).

The normal light and brick houses, constructed of thin hollow wood panels or simple bricks, serve as a reference: they are typical for traditional economic housing in Chile with no fixed shading, simple curtains, simple glazing, no insulation, constant ventilation of 3ach in summer and high infiltration of 1,5ach in winter.

They present severe thermal comfort problems in both seasons, though even worse constructions than here could easily be found (cf. figures 2 to 5). The two groups of these houses show the negative influence of their typically arbitrary orientation (with minor differences between east and west not shown).

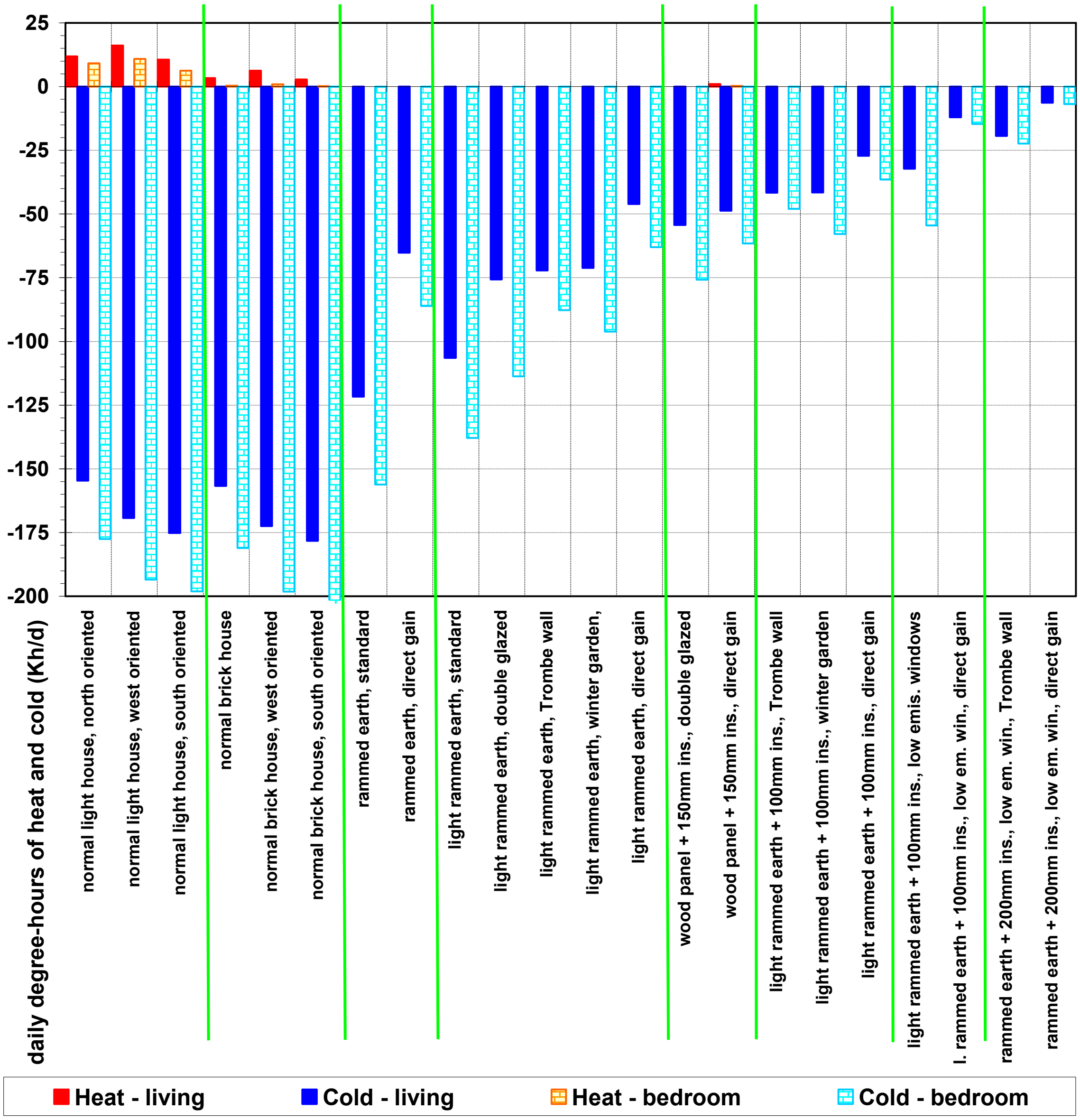

Fig. 11: Comparison of the thermal behavior of normal, improved and passive houses for Santiago de Chile: daily degree hours of heat and cold for hot period (12~2, base 26°C, >0) and cold period (5~9, base 19°C, <0) for living room and bedroom (bedroom option: Trombe wall; both with option winter garden)

The other “standard” proposals have an optimized roof overhang, better curtains for solar protection in summer and at least 80mm of roof insulation. The standard house with rammed earth walls still has simple glazing, but only 1ach of infiltration and night ventilation in summer, resolving problems in summer but still deficient comfort conditions in winter, that can be reduced with larger, direct gain windows.

A first set of simple passive houses, made of light rammed earth with better insulation characteristics (due to low density) and better windows, demonstrates that, depending on the technical and financial effort, it is possible to design simple passive houses for a mediterranean climate which can offer improved thermal comfort during the whole year. Trombe walls are thermally less efficient, but offer the earthquake resistance of massive walls if their ventilation openings are reinforced appropriately, whereas a winter garden offers additional living space, but direct gain windows present the thermally most efficient solution in winter. Insulated wood panel houses (with heavy floor) offer similar efficiency in winter, but can present some problems in summer due to their lower thermal capacity. Light rammed earth with 100mm additional external insulation offers some additional but still incomplete improvements in all three cases.

Light rammed earth with low emissivity double glazing and 100mm or 200mm additional external insulation in the direct gain design finally can offer really passive solutions for summer and winter (except a few cold hours especially in the morning when lower temperatures are acceptable). Thanks to careful design, this can be achieved with a still reasonable technological level for an emerging economy and without the necessity of complicate and/ or non-renewable energy consuming active systems.

This way, the comparison in figure 11 offers a second and comprehensive proof that passive design is possible in this climate region. As discussed in the introduction, this had not been shown systematically and based on hourly thermal simulations with a test year for Chile before. It is confirmed that passive design is possible here without the need of non-renewable energy for thermal purposes or complicate installations, offering good thermal comfort conditions both in the hot and cold period of the year.

3.3. Resume of design recommendations for passive houses in a Mediterranean climate

The crucial building parameters and extensive simulation and analysis of both reference rooms and complete houses permit the optimization of passive design projects and the formulation of design recommendations, based on an improved qualitative and quantitative understanding of thermal building dynamics:

- For the whole year, it is important to have a large time constant τ with sufficient thermal mass in floors and walls to reduce both overheating in summer and make efficient use of solar gains in winter (heavy ceilings are not recommendable in seismic zones). Thermal insulation of the roof/ceiling is always important, both in the hot and cold period. The recommended orientation for the main façade with the largest windows is towards the equator and winter midday sun (north in the southern hemisphere, south in the northern hemisphere). Such windows receive much less solar radiation in summer than in winter due to the seasonal variation of solar declination and altitude and can receive selective fixed solar protection by overhangs.
- In the cold period the recommended strategy is to increase the effective-gains-to-loss ratio GLeff. This requires reducing heat losses with thermal insulation (on walls, windows and roof/ceiling) and increasing solar gains in an equilibrated way, combined with a sufficient thermal mass permitting good utilization of passive gains. The reduction of ventilation losses through infiltrations from windows and doors is an important part of low heat losses and is only possible when internal contamination from heating systems is avoided in a passive house. High solar gains during the day are only effective if they can be accumulated for colder hours in thermal mass. Especially recommended elements are large window areas of high quality for increased direct solar gains on the north façade, but winter gardens and Trombe walls for indirect gains are interesting solutions as well.
- In the hot period the recommended strategy is to minimize the excess-gains-to-loss ratio GLexc. This requires the limitation of solar gains with efficient solar protection from fixed shading by carefully designed horizontal overhangs on the north façade (on relatively low latitudes in the southern hemisphere) and effective mobile shading on all windows. A high thermal capacity and appropriate (protected) external and internal openings permit effective night ventilation.

4. Conclusions

The design recommendations for simple and advanced passive houses now show that with an optimized design it's possible to improve significantly the thermal comfort conditions in economically accessible dwellings of the region. Thermal energy use can be limited to renewable sources, mainly solar energy. The methodology and approach developed are extendable to other regions and similar climate zones of Latin America and emerging countries. Hopefully this will contribute to the further diffusion of solar and passive housing as an important element of sustainable development.

5. Acknowledgments

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Environmental Commission CONAMA, both in Santiago de Chile. The program DEROB-LTH could be used thanks to the cooperation with Lund University (Sweden) for the PhD.

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