PROBABILISTIC ASSESSMENT OF DISCOMFORT RISK IN BUILDINGS

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ABSTRACT

Along with the outdoor climate, building design, materials and construction system determine the thermal behaviour of buildings, the ability to keep indoor comfort conditions and the energy consumption through their lifespan. Buildings must provide comfortable indoor environment which should be reasonably assured regardless of climatic fluctuations. This paper presents a novel methodology for quantifying the hygrothermal discomfort risk of any building design. By means of a numeric model of the building hydrothermal response and stochastic simulation techniques, the expected frequency and duration of discomfort events in each building room and the probability distribution of energy consumption associated to heating and cooling can be estimated. The article presents fundamentals on hygrothermal risk assessment, the numerical simulation models and the developed reliability indexes. In order to illustrate the proposed approach in the context of the design process, the methodology was applied to a prototype of a residential house conventionally built and acclimatized. The materials and construction reflect typical residential housing in the region of study. A bioclimatic variant of the same building is also evaluated. Monte Carlo simulations under stochastic climate conditions allow identifying infrequent but important situations in which the building is unable to meet comfort requirements. Statistical analysis of simulation results is performed and condensed in meaningful reliability indices. By means of these indicators, shortcoming of the architectonic design can be revealed and properly solved. In addition, quantitative comfort reliability indices facilitate the comparison of different thermal building designs on the same basis. The proposed methodology and the developed models can be applied without constraints to any building design under a wide variety of climates.

1. INTRODUCTION

It has been proved that buildings are intensive energy consumers in all countries, especially due to the operation of HVAC equipment. In Argentina, buildings represent 40% of the overall energy consumption, 90% of which is supplied from non-renewable sources (Evans, 2010). Residential and commercial buildings account for almost 39 percent of total U.S. energy consumption and 38 percent of U.S. carbon dioxide (CO2) emissions. Nearly all of the greenhouse gas (GHG) emissions from the residential and commercial sectors can be attributed to energy use in buildings (DOE, 2008). The consumption of heating and cooling can be reduced principally through the correct morphologic design, favourable orientation and the appropriate selection of building envelopes and their components (Filippín, 2005). The implementation of bioclimatic strategies (BS) in building design aims at maintaining comfortable indoor conditions as much time as possible while minimizing conventional energy consumption.

Buildings are subject to changing climactic conditions. Part of the climate variability is stochastic in its very nature and introduces considerable uncertainty in resulting hygrothermal indoor conditions as well as in the effectiveness of certain BS (Boland, 1997). Buildings have to preserve indoor comfort, regardless of the severity and persistence of adverse outdoor climate. The problem with bioclimatic design is the high dependence of performance on outdoor climate and the consequent introduction of uncertainty in building behavior. For example, in the use of solar heating, there is a negative correlation between the outdoor solar energy and the indoor heating requirement.

Therefore, one of the questions that arises within the bioclimatic building design process is how reliable and effective are the BS for ensuring pre-established comfort conditions in the presence of fluctuating and random climatic situations, both in terms of severity and duration. In the last years, there have been diverse attempts to include the stochastic variables, especially climactic, in the hygrothermal building simulation (Jiang, Hong, 1993). Bzowska (2002) calculates the mean value and the standard deviation of indoor temperature with a simple two-node simulation model. This methodology proposes the superposition of deterministic and stochastic outdoor climate variables for simulation. Pietrzyk (2000) develops an analytic probabilistic model with for the estimation of air infiltration and heat loss in houses. The work emphasizes the importance of considering reliability in building design. However, it analyzes the stochastic building behaviour without considering the chronology of events, which in turn ignores autocorrelation and dependency of climatic changes. In addition, important temporally coupled phenomena such as the thermal inertia in the thermodynamics of constructions are disregarded. Inherently, the analytical reliability models are computationally very efficient, thought substantial simplifications are often required to obtain workable solutions. In comparison, simulation models based on Monte Carlo techniques do not normally require simplifications allowing a detailed description of reality. However, they have the disadvantage of being very expensive in computational calculations (Mechri et al. 2010).

The present paper shows a new methodology to evaluate the level of hygrothermal reliability of any building design (Sulaiman, 2001). By means of a numeric model of the building hydrothermal response and stochastic simulation techniques, the expected frequency and duration of discomfort events in each building room and the probability distribution of energy consumption associated to heating and cooling can be estimated. This probabilistic analysis enables the proper evaluation and comparison of the thermal performance of various design alternatives on the same basis. Furthermore, it also allows placing discomfort risk constraints restrictions on the economic optimization of the thermal design, while avoiding over-or under-sizing of HVAC equipment, envelope insulation, thermal mass and solar collection surface.

The paper is organized as follows: first, the essential concepts on thermal reliability evaluation and discomfort risk assessment of buildings are introduced. Next, the reliability indices and the developed risk metrics and the criteria for defining are presented. Numerical models for stochastic simulation are described in Section IV. In Section V, the practicability of the proposed methodology is illustrated in an exemplary residential dwelling. The differences in energy consumption computed under deterministic and stochastic conditions are analyzed. Finally, conclusions and avenues for further investigation are provided in Section VI.

2. HYGROTHERMAL COMFORT RELIABILITY

In the present paper, Hygrothermal Comfort Reliability (HCR) has been defined as the capability of an architectonic design, whether conventional, bioclimatic or hybrid, to maintain pre-established hygrothermal comfort indoor conditions in the presence of random exterior climate fluctuations. HRC can be expressed as the probability that the building preserves indoor conditions within a given comfort zone. Reliability design is an engineering approach widely used in nuclear energy systems (Zio, Pedroni, 2009), in the aerospatial industry (Epstein et al., 2006), power systems (Olsina, 2005), sizing of civil structures (Lagaros et al. 2008), etc. In this paper, an extension of this approach to the hygrothemal building design is proposed.

The probability that a building satisfies the hygrothermal requirements will depend on its topological and morphological design, orientation, solar capitation surface, constructive materials and components, HVAC installed capacity and the severity of the local climate. In addition, the imposed constraints on the range where the indoor conditions can fluctuate have also a significant impact on the probability of satisfying the hygrothermal requirements. Hence, an acceptable comfort zone must be established with extreme caution according to the function and use of the building (for example: house, office, gym, hospital, museum, library, archive, etc.) and of each room (for example: bedroom, reading room, intensive care room, warehouse, etc.).

The comfort area can be defined in term of maximum and minimum acceptable limits for temperature and humidity, setting therefore a two-dimensional region for assessing the compliance of given a thermal design. The comfort region is usually established according to specific standards and norms on human comfort. An example of this would be proving that a certain architectonic design should be keep indoor conditions within the specified comfort region at least 95% of the time, during which 75% of people feel comfortable according to ASHRAE Standards (2005).

Last but not least, the established maximum admissible disconfort risk will determine the essential features of the thermal design and the required initial investments and energy costs for the operation of heating and cooling equipment. Therefore, the minimum reliability level must also be carefully selected in order to avoid adversely affecting the economy of the building.

3. RELIABILITY AND RISK INDICES

In order to provide a quantitative description of the thermal reliability level and the discomfort risk, a set of probabilistic indicators are proposed. HCR is usually expressed as a probability, but it can also be given in terms of the expected annual cumulated time, i.e. hours per annum [h/a], the building satisfies the imposed conditions of comfort. Sometimes, it is convenient to use the complementary concept of Hygrothermal Discomfort Risk (HDR), defined as the probability that the building does not keep indoor conditions within the pre-established comfort region. Since hygrothermal conditions of a building can only reside in two mutually exclusive states –acceptable or unacceptable,– HDR is determined according to the complementarity identity: HCR + HDR = 1.

Although HDR indicates the probability of occurrence of discomfort events, it does not reflect their magnitude. Therefore, it is common to use HDR in conjunction with complementary indicators. The expected value of indoor temperature and humidity during discomfort events reflects the magnitude of deviations (violations) in comparison with the limits of the established comfort region.

Other meaningful indicators which, together with the indicators mentioned above, provide a better understanding of the reliability level and the hygrothermal risk of a certain architectonic design are the expected occurrence frequency of discomfort events (LOCF), expressed, for example, as per year occurrences [a^{-1}], and the expected duration of discomfort events (EDDE) in [h]. The designer could evaluate and decide whether, in a certain building and considering the purpose, it is preferable to accept a greater number of duration discomfort events but of shorter duration r, or accept one or two lengthy events (such as 2 or 3 consecutive days). The duration and frequency indices can be disaggregated in four specific indices to indicate the cause of occurrence and the deviating direction regarding each limit of the defined comfort zone. Therefore, there will be indicators for the violation of the upper and lower limits of the admissible temperature and humidity. Similarly, each of these indicators can be estimated for the whole annual period or for only certain seasons, months or hours of the day. The disaggregation of the reliability indices provides relevant information about the type and cause of the building reliability problems, favoring the fast identification of solutions in the design optimization process.

Figure 1 represents, in a small number of days, the events that define most of the indices for temperature. Outside the comfort zone (CZ), there are moments that exceed the limits due to overheating (OvH) or moments in which the minimum temperature is not reached (UnH). In those moments, there is a d duration and a deviation from the CZ limit. Expected OvH or UnH values account for the average of these deviations on the number of simulated samples. The mean of the d duration determines the expected duration of EDD discomfort events. The frequency, identified as LOCF, is the mean amount of discomfort events per time unit, for example, in one year, calculated over the simulated sample.

Threshold Definition Criteria

Range	T (C°)	RH (%)	HCR (%)	HDR (%)	EDD (h/a)	EDDE (hs)	LOCF (1/a)	EUnH (C°)	EOvH (C°)	EUnRH (%)	EOvRH (%)
min.	19	30	95	0	0	0	0	18.9	26.1	29	71
max.	26	70	100	5	438	5.84	75	15.9	29.1	20	80

Table 1. Thresholds suggested for a house

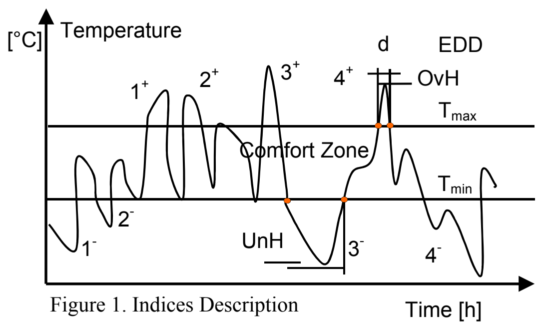


Figure 1. Indices Description

Depending on the hygrothermal requirements of the building designed, it is possible to establish certain thresholds for most of the indices developed. Table 1 includes an example of the thresholds suggested for a conventional house that were considered in the application that was made. In those cases in which there is a continued use of the building, the criterion would be not to distance so much from the limits imposed and not to do it over so prolonged periods of time. Nonetheless, the range of temperatures and relative humidity corresponding to 75% of comfortable people according to ASHRAE Standards (2005) has been established. It comprises temperatures ranging from 19 to 26°C, and RH ranging from 30 to 70%, which can be considered sufficiently flexible. Minimum HCR of 95% implies that indoor hygrothermal conditions must reside within the prefixed comfort zone, at least, 95% of the time. It is possible to establish one or more conditions simultaneously, for example, a 5% HDR would equal a maximum amount of 438 h outside the CZ (EDD.) Due to the continued use of the house, it might be possible to admit several discomfort events (LOCF) but with a short duration (EDDE).

4. NUMERICAL MODEL

In order to identify the possible occurrences of discomfort events when designing a building that will be exposed to certain climate conditions, it is necessary to use numerical models that replicate the indoor hygrothermal dynamics under a chronological series of meteorological conditions. The thermal model of a building must reproduce thermodynamics phenomena such as heat transference conduction, convection and radiation and the mass transport such as ventilation and people traffic. Moreover, the simulation model must consider the accumulation of heat in the mass of the building (thermal inertia) that dampens the influence of outdoor climactic fluctuations in the room conditions besides originating a temporal coupling of indoor conditions between adjacent intervals of time.

Ideally, the model should also account for both the interaction between temperature and relative humidity and the phenomenon of moisture accumulation and exchange that is latent in furniture, curtains, wood, etc. Due to its open source design, the HAMBASE simulation model (Wit, 2006) which considers all the mentioned phenomena has been selected for this application. Building features, such as number of rooms, morphology, orientation, materials, and heating and cooling equipment must be entered as input data. As a result, a chronological time series of temperature and humidity in each room as well as the energy consumption for heating and cooling can be obtained.

For the design being analyzed, the number, duration and magnitude of discomfort events will depend on the particular year used as input data in the simulation. In order to obtain statistically meaningful results, an ensemble with a large number of sample years must be considered. This allows exploring the thermal behavior of the building under infrequent but severe climatic conditions. If there is no availability of enough climate information on the locaton of interest, a synthetic climate database must be generated based on the existent observational record. The statistical evaluation of the hourly hygrothermal conditions in each room resulting from massive simulation of annual meteorological scenarios enable the estimation of the reliability indices and discomfort risk of the design under analysis. The advantage of stochastic simulation techniques (Monte Carlo method) is that a problem can be solved without simplifications. The disadvantage is the intensive use of computational resources. This disadvantage, however, has been progressively mitigated due to the rapid growth of computing power. Furthermore, because of Monte Carlo is loosely coupled computation technique amenable to distributed computing, the multi-core architecture of modern processors can be advantageously exploited for drastically reducing calculation time.

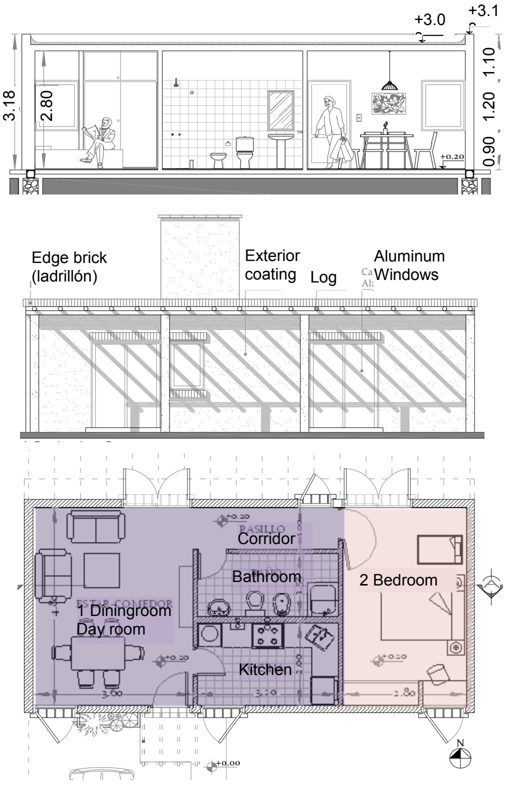


Figure 2 Plant, North view and house plan, 2 hygrothermal zones (1 day room, 2 bedroom)

5. APPLICATION TO A RESIDENTIAL HOUSE

With the purpose of demonstrating the applicability of the proposed methodology, the hygrothermal reliability of a residential dwelling is assessed.

CovnHouse and BioHouse Construction Description	Espesor m²	Sup. m²	K (W/°C m²)
Ladrillón wall 0.17 m + coat on both sides	0.20	47.40	1.97
Same as above + 0.05 m polystyrene 15 kg/m² + edge brick (ladrillón) 0.07 m	0.32	34.00/ 13.40*	0.53
Inner non-supporting partition	0.12	37,50	-
Pre-stressed ceramic slab + 0.02 m concrete with perlite	0.22	47.04	2.64
Same as above + 0.08 m concrete with perlite	0.30	47.04	0.83
Ceramic floor, subfloor, natural land (Per. 29.8 m)	0.20	47.04	1.38
Doors (pine wood)	0.04	1.80	2.29
Single glass 6 mm windows	0.05	10.60	5.70
Single glass with closed shutter	0.01	12.80	2.80
Natural ventilation acclimatization, 2000 W of H and AC per zone	**G cal (W/m³°C)**	**1.72**	**B:1.71**
Same as above + humidification		**1.43**	**C: 2.00**

X: 9.30, Y: 4.80, Z: 2.80 – Covered surface in m²: 46.08 - with walls: 52.52 - Vol.: Z1 in m²: 94.08 - Vol. Z2: 37.6

*same wall as ConvHouse (boundary, attached)

Table 2 ConvHouse and BioHouse description

Construction as well as heating and cooling systems are conventional (ConvHouse). In addition, a modified design variant which includes bioclimatic strategies (BioHouse) is also considered for the sake of comparison. Both buildings are subject to a dry hot (summer) and a dry cold (winter) representing the climate prevailing in the City of San Juan, Argentina (31°32′S 68°31′W). ConvHouse (c.f. Fig. 2) is paired (in this case, adiabatic wall in West), all rooms are well-oriented, the north façade receive solar gain (12.5% useful surface), excluding bathroom and kitchen. The orientation East and West are blocked, it has North solar protection. Also there are protection from cold winds from sector South by means of regular windows with shutters. Total thermal mass is 4.41 kWh/K (zone 1) and 2.19 kWh/K (zone 2), calculated with HAMBASE. Table 2 presents construction features, thermal transmittance U, and calculated global loss coefficients G, where the modifications introduced to the BioHouse become evident.

ConvHouse

Figure 3 shows the ConvHouse scheduled simulation of indoor temperature and relative humidity, together with outdoor climate conditions in one year. Although temperatures are predominantly acceptable, Zone 1 often loses comfort during the winter and, to a lesser extent, in summer. Relative humidity, on the other hand, decreases in winter because of the heating system, whereas it coincides with outdoor peaks in summer, with considerable instability.

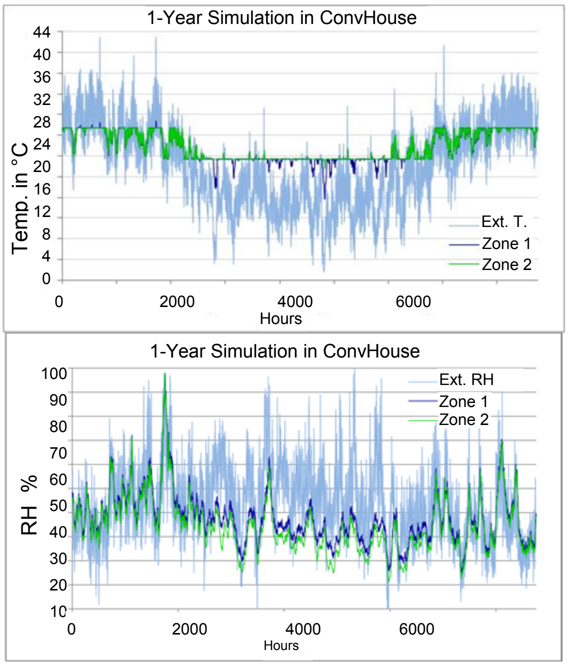
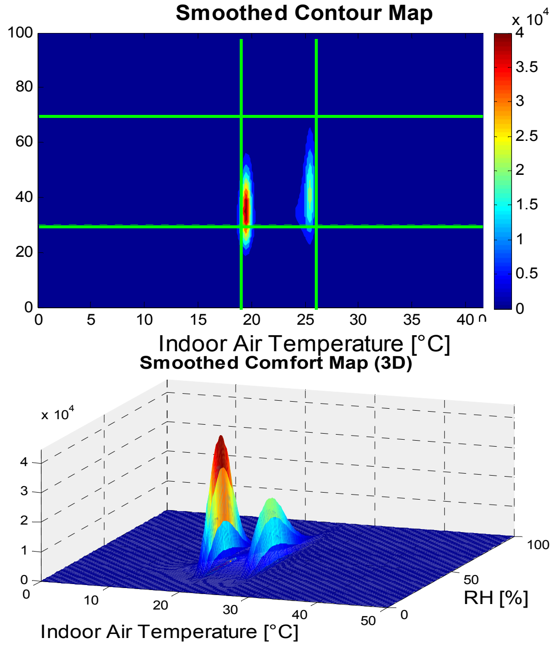


Figure 3 ConvHouse 1-year simulation in with outdoor

Discomfort Risk Indices

Index	Units	Zone 1
HCR	[%]	71.5
HDR	[%]	28.5
EDD	[h/a]	2496
EUnH	[°C]	17.4
EOvH	[°C]	27.1
EUnRH	[%]	25.3
EOvRH	[%]	77.2
EDCE	[h]	82
EDDE	[h]	33
ELCF	[a^{-1}]	76.5



It is worth noting that, in Figure 4, there is a low reliability level achieved through conventional acclimatization (HCR=71.5%, HDR=28.5%) since there is almost 2500 h/a where the house cannot maintain indoor comfort conditions, whether because of a distancing from temperature or relative humidity levels or both levels at the same time. The mean duration of discomfort events (EDDE) is 33 h and the annual frequency of discomfort events (ELCF) is 76.5 a-1. As Figure 4 shows, indoor climate spreads over two long areas in the upper and lower temperature limits, extending across almost the whole RH range.

Figure 5 shows the statistical convergence of the ConvHouse HDR estimation where, although a fast stabilization is noticed, a simulation of at least 500 years becomes necessary. Moreover, the difference in HDR for each zone is highlighted (Zone 1: 28%, Zone 2: 36%).

Figure 6 allows the detection of deficiencies in hygrothermal comfort in an accurate and differentiated manner. In ConvHouse Zone 1, the higher percentage of reliability loss is due to dehumidification during the winter with a 40.87% probability of being below the minimum established, achieving an expected average relative humidity of 32%. In the second place and with a probability of approximately 18.5%, indoor temperature during the winter is the cause of discomfort. However, when observing this graphic in conjunction with the EUnH index (Figure 4), the temperature below the limit is on average 17.4°C, that is, only 1.6°C below the 19°C limit. Patterns that are considered constant, such as increased use of warm clothing, internal gains, activity and installed heating capacity could be modified, or envelopes could be improved for energy conservation.

The average value of indoor temperatures during the winter is 19.4°C and the distribution of probabilities is similar to the normal distribution; therefore, comfort conditions are mainly attributable to acclimatization due to the poor quality of envelopes. As for relative humidity, the addition of a humidifier is required to reach humidity conditions within the comfort band. When considering the probabilities of being outside the comfort zone, in summer, RH shows a 6.9% deficit and exceeds the maximum acceptable value by 4%. In summer, comfort is

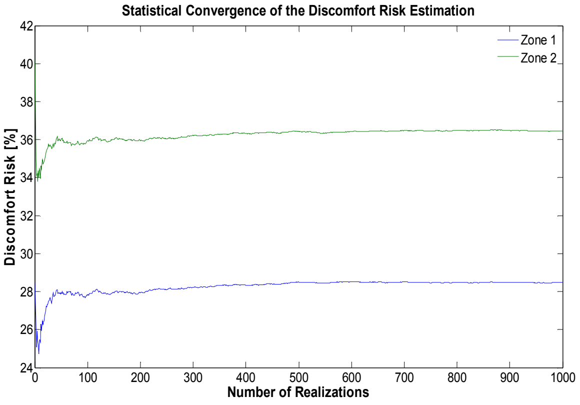


Figure 5: statistical convergence in ConvHouse HDR

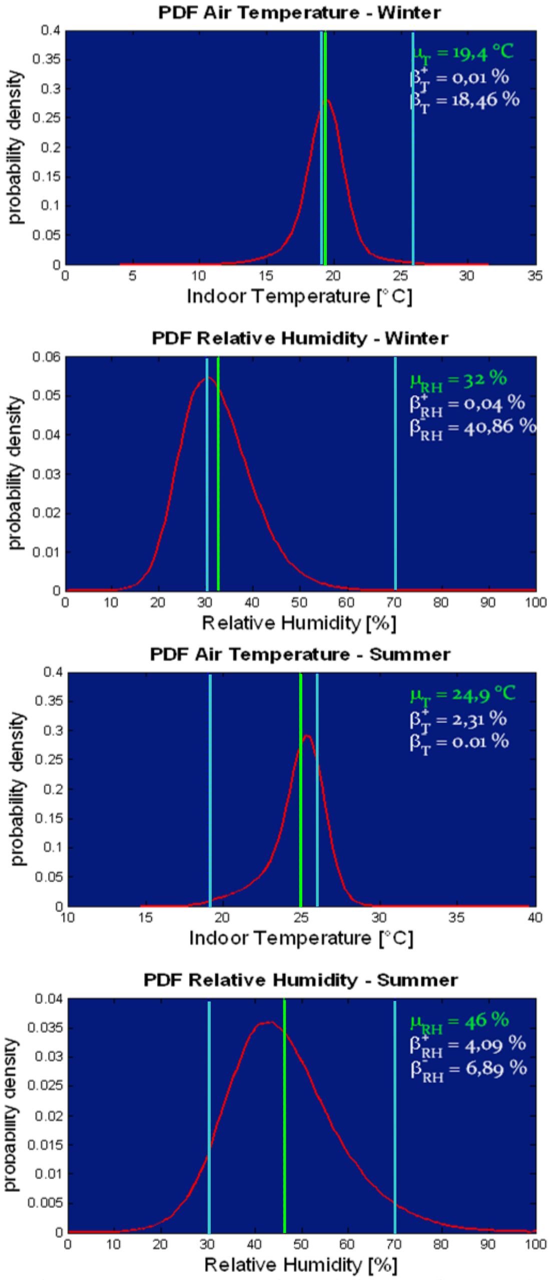


Figure 6: temperature and RH (winter and summer) PDF of ConvHouse Zone 1

higher although there is a higher dispersion of temperature and humidity, which would cause discomfort because of the indoor daily range. Dispersion in the distribution of winter RH is lower than in summer, when registered values are among 10 and 90%, with 46% expected mean. To summarize, the reliability achieved is high, though not enough, due to the construction features in the analyzed design (envelope

admitted by the effective building code).

BioHouse

Figure 7 shows the behavior of indoor temperature and relative humidity in BioHouse for the same simulated year. On the one hand, there is absence of hours outside the established temperatures, and on

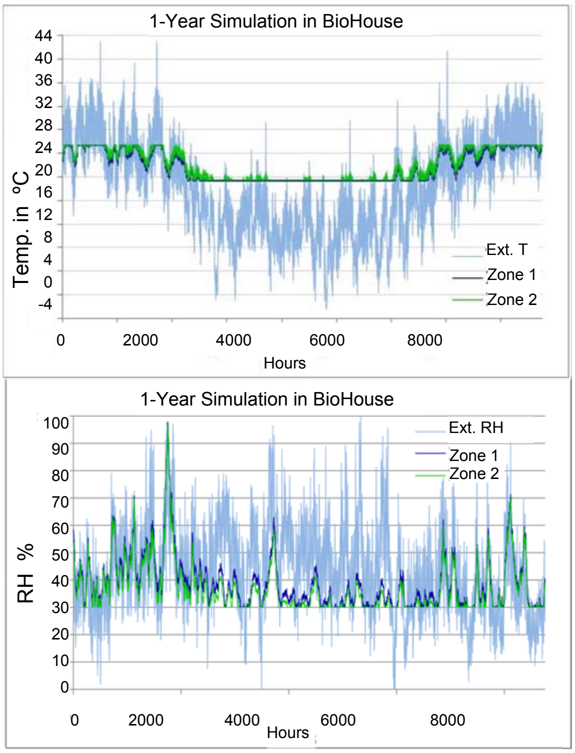
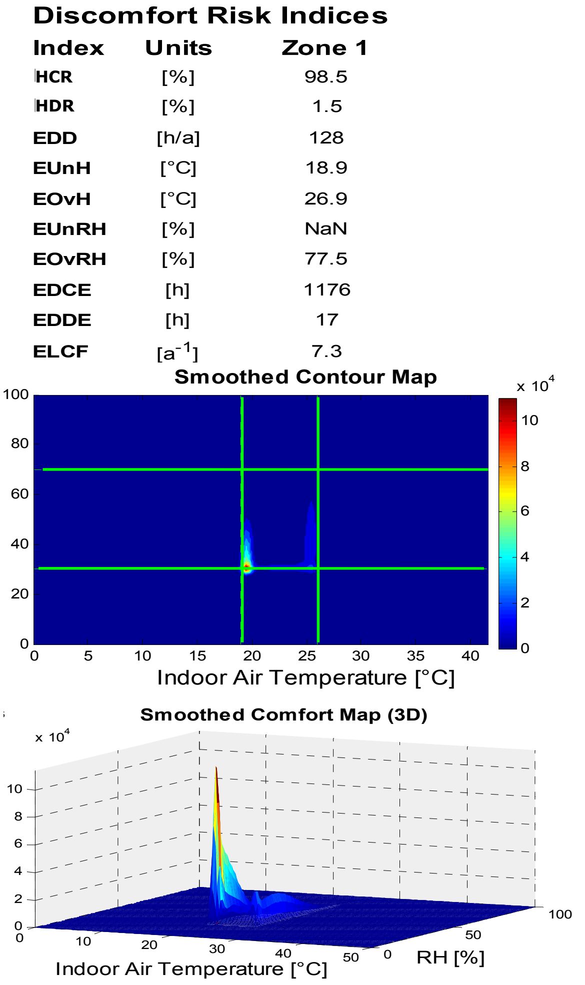


Figure 7: BioHouse 1-year simulation & outdoor climate


Discomfort Risk Indices

Index	Units	Zone 1
HCR	[%]	98.5
HDR	[%]	1.5
EDD	[h/a]	128
EUnH	[°C]	18.9
EOvH	[°C]	26.9
EUnRH	[%]	NaN
EOvRH	[%]	77.5
EDCE	[h]	1176
EDDE	[h]	17
ELCF	[a^{-1}]	7.3

Figure 8: BioHouse reliability indices and comfort map in zone 1

the other hand, there is controlled humidity in the lower limit of the comfort region established. However, it is necessary to revise the design to avoid the instability caused by an excess in RH since it reaches 97% in March (day 73) and exceeds 70% in repeated opportunities. Figure 8,

shows reliability indices, and 2D and 3D comfort maps where temperatures adopt two lineal zones interior to the limits, indicating a higher density point in minimum RH, due to humidifier activity. According to the indices, this architectonic design reaches a high

reliability level (98.5% HCR, with an expected accumulated duration of discomfort events of 128 h per year), in which the risk is mainly due to an excess in RH during the summer and overheating in the same period. The 3D comfort map reflects a significant peak in the 20°C zone and 31% humidity, indicating that these are the most likely indoor conditions.

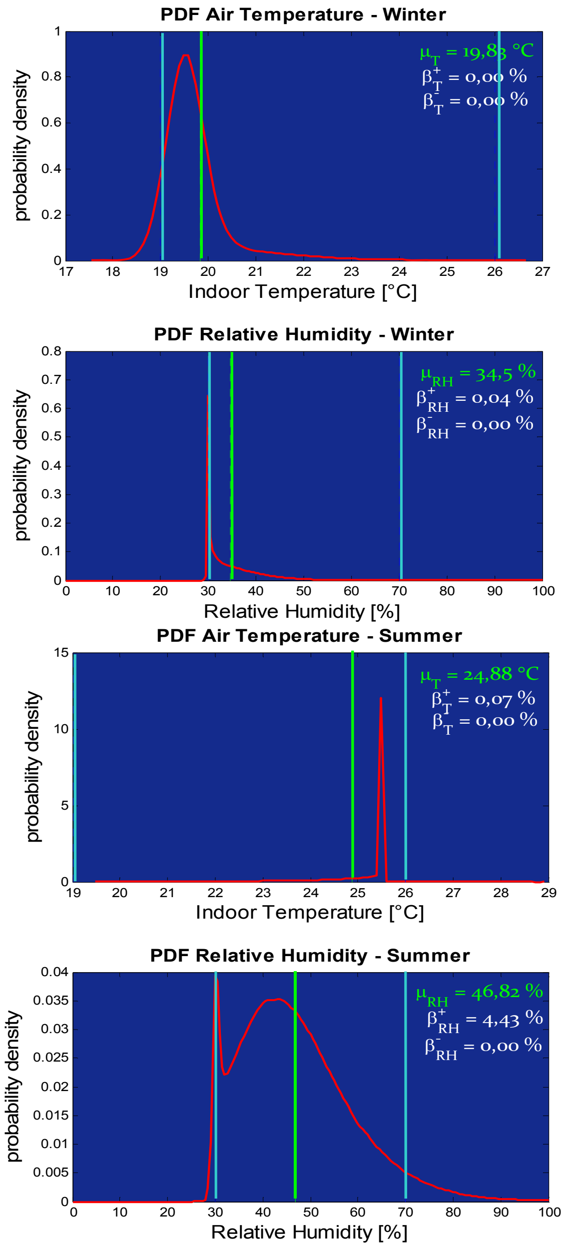


Figure 8: PDF, T and RH μ and ß for summer and winter in BioHouse Zone 1

In Figure 8, ß shows that, in winter, temperatures do not fall below 19°C and just 0.07% is above 26°C in summer, indicating that the thermal comfort objectives proposed are achieved in 99,93%. Average values are 19.8°C and 24.9°C in winter and summer, respectively. RH features comfort more than 95.5% of the time, whereas in summer the upper limit is exceeded with a 4.7% probability. It can be stated that, with the addition of a dehumidifier, usually contained in the cooling equipment, HCR could reach 100% (with an unknown AC equipment failure probability).

The methodology proposed is proved to allow the quantification of the discomfort risk that could be implied by modifications in the hygrothermal design.Table 4 shows the expected annual energy consumption in both houses and an energy saving of 59,9% can be observed in the bioclimatic house, compared to the conventional house.

6. COMPUTING TIME

The simulation times needed in function of the amount of realizations required. With a 8 GB and 4 CPU capacity, a stochastic simulation of 1000 years of this example of house with 2 hygrothermal zones requires 52,8 minutes. the time simulation of a hourly year consume 30 seconds. The optimization carried out in Sulaiman (2011) has evaluated 100 differents designs 300 years ich one. It was necessary more than 26 hs in totally computing.

7. CONCLUSIONS

The present paper proposes a methodology to quantitatively evaluate the hygrothermal reliability of a building design, based on stochastic simulation of the building hygrothermal behavior. The methodology proposed allows to quantify the uncertainty of the building indoor conditions and discomfort risk, while considering the random nature of outdoor climate. Similarly, it is possible to quantify the energy consumption expected for acclimatization during the building lifespan. A number of probabilistic indicators have been developed to characterize the reliability level. These indicators can be used as restrictions accepted during the building hygrothermal design process and its optimization.

The methodology proposed has required the development of computing routines and climatic databases for its implementation, not only for the present application, but also for future studies. For this purpose, a stochastic simulation model named sHAMs (stochastic Heat And Moisture simulation) was created. With this model, the reliability and comfort of a building (bioclimatic, hybrid or conventional) and the discomfort risk under climatic condition variations in the implantation site can be determined. SHAMs is supported by the same platform (MatLab) as HAMBASE, the hygrothermal simulation program used, which has allowed the integration of both, the treatment of input and output data in other formats commonly used, and the graphic processing of results that facilitates their interpretation. At the same time, the methodology allows the possibility of adding other independent modules to make the hygrothermal and economy analysis of buildings more in-depth and greater in scope, with the purpose of applying numerical optimization in Architecture.

Graphic visualization tools have also been developed as they are very helpful in this process. The three-dimensional representation by season allows to modify the design until it satisfies the maximum acceptable hygrothermal risk conditions. Hence, it is possible to measure thermal mass, insulation thickness, acclimatization equipment capacity, size of openings, etc., so that the total building cost (investment costs and acclimatization future costs) is minimum.

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