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Regression Models to Assess the Thermal Performance of Brazilian Low-Cost Houses: consideration of opaque envelope

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DEDICATION

To God, Who grants the wisdom.

To my parents, Valmor and Aparecida, which are my great examples.

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ABSTRACT

FAVRETTO, A. P. O. **Regression Models to Assess the Thermal Performance of Brazilian Low-Cost Houses**: consideration of opaque envelope. 2016. 132 p. Thesis (Master of Science) – Institute of Architecture and Urbanism, University of São Paulo, São Carlos, 2016.

This study examines the potential to conduct building thermal performance simulation (BPS) of unconditioned low-cost housing during the early design stages. By creating a set of regression models (meta-models) based on EnergyPlus simulations, this research aims to promote and simplify BPS in the building envelope design process. The meta-models can be used as tools adapted for three Brazilian cities: Curitiba, São Paulo and Manaus, providing decision support to designers by enabling rapid feedback that links early design decisions to the building's thermal performance. The low-cost housing unit studied is a detached one-story house with an area of approximately 51m², which includes two bedrooms, a combined kitchen and living room, and one bathroom. This representative configuration is based on collected data about the most common residence options in some Brazilian cities. This naturally ventilated residence is simulated in the Airflow Network module in EnergyPlus, which utilizes the average wind pressure coefficients provided by the software. The parametric simulations vary the house orientation, U-value, heat capacity and absorptance of external walls and the roof, the heat capacity of internal walls, the window-to-wall ratio, type of window (slider or casement), and the existence of horizontal and/or vertical shading devices with varying dimensions. The models predict the resulting total degree-hours of discomfort in a year due to heat and cold, based on comfort limits defined by the adaptive method for naturally ventilated residences according to ANSI ASHRAE – Standard 55. The methodology consists of (a) analyzing a set of Brazilian low-cost housing projects and defining a geometric model that can represent it; (b) determining a list of design parameters relevant to thermal comfort and defining value ranges to be considered; (c) defining the input data for the 10.000 parametric simulations used to create and test the meta-models for each analyzed climate; (d) simulating thermal performance using Energy Plus; (e) using 60% of the simulated cases to develop the regression models; and (f) using the remaining 40% data to validate the meta-models. Except by Heat discomfort regression models for the cities of Curitiba and São Paulo the meta-models show R^2 values superior to 0.9 indicating accurate predictions when compared to the discomfort predicted with the output data from EnergyPlus, the original simulation software. Meta-models application tests are performed and the meta-models show great potential to guide designers' decisions during the early design.

KEY WORDS: Thermal comfort, Building performance simulation, Regression model, Low-cost housing.

RESUMO

FAVRETTO, A. P. O. **Modelos de regressão para avaliação do desempenho térmico de habitações de interesse social**: considerações da envolvente opaca. 2016. 132p. Dissertação (Mestrado) – Instituto de Arquitetura e Urbanismo, Universidade de São Paulo, São Carlos, 2016.

Esta pesquisa avalia as potencialidades do uso de simulações do desempenho térmico (SDT) nas etapas iniciais de projetos de habitações de interesse social (HIS) não condicionadas artificialmente. Busca-se promover e simplificar o uso de SDT no processo de projeto da envolvente de edificações através da criação de modelos de regressão baseados em simulações robustas através do software EnergyPlus. Os meta-modelos são adaptados ao clima de três cidades brasileiras: Curitiba, São Paulo e Manaus, e permitem uma rápida verificação do desconforto térmico nas edificações podendo ser usados como ferramentas de suporte às decisões de projeto nas etapas iniciais. A HIS considerada corresponde a uma unidade térrea com aproximadamente 51m², composta por dois quartos, um banheiro e cozinha integrada à sala de jantar. Esta configuração é baseada em um conjunto de projetos representativos coletados em algumas cidades brasileiras (como São Paulo, Curitiba e Manaus). Estas habitações naturalmente ventiladas são simuladas pelo módulo Airflow Network utilizando o coeficiente médio de pressão fornecido pelo EnergyPlus. As simulações consideram a parametrização da orientação da edificação, transmitância térmica (U), capacidade térmica (Ct) e absortância (α) das paredes externas e cobertura; Ct e U das paredes internas; relação entre área de janela e área da parede; tipo da janela (basculante ou de correr); existência e dimensão de dispositivos verticais e horizontais de sombreamento. Os meta-modelos desenvolvidos fornecem a predição anual dos graus-hora de desconforto por frio e calor, calculados com base nos limites de conforto definidos pelo método adaptativo para residências naturalmente ventiladas (ANSI ASHRAE, 2013). A metodologia aplicada consiste em: (a) análise de um grupo de projetos de HIS brasileiras e definição de um modelo geométrico que os represente; (b) definição dos parâmetros relevantes ao conforto térmico, assim como seus intervalos de variação; (c) definição dos dados de entrada para as 10.000 simulações paramétricas utilizadas na criação e teste de confiabilidade dos meta-modelos para cada clima analisado; (d) simulação do desempenho térmico por meio do software EnergyPlus; (e) utilização de 60% dos casos simulados para o desenvolvimento dos modelos de regressão; e (f) uso dos 40% dos dados restantes para testar a confiabilidade do modelo. Exceto pelos modelos para predição do desconforto por calor para Curitiba e São Paulo, os demais meta-modelos apresentaram valores de R^2 superiores a 0.9, indicando boa adequação das predições de desconforto dos modelos gerados ao desconforto calculado com base no resultado das simulações no EnergyPlus. Um teste de aplicação dos meta-modelos foi realizado, demonstrando seu grande potencial para guiar os projetistas nas decisões tomadas durante as etapas inicias de projeto.

PALAVRAS CHAVE: Conforto térmico, Simulação do desempenho de edificações, Modelos de regressão, Habitações de interesse social.

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LIST OF ABBREVIATIONS, ACRONYMS AND SYMBOLS

R_a: Thermal resistances of outer air film

R_i: Thermal resistances of inner air film

R_T: Ambient to ambient total thermal resistance

R_t: Surface to surface thermal resistance

BPS: Building performance simulation (BPS)

c: Specific heat

DH_C: Degree-hours of discomfort by cold during a year

DH_H: Degree-hours of discomfort by heat during a year

HC: Heat capacity

l: Thickness

LCH: Low-cost houses

OE: Opaque envelope

r: Reflectivity

R: Thermal resistance

U-value: Thermal transmittance

α: Solar absorptance

λ: Thermal conductivity

ρ: Apparent density

1. INTRODUCTION

The search for mechanisms to promote and ensure live quality has been occurring throughout the history of civilization. The building of shelters against bad weather conditions or other threats and the implementation of thermal comfort strategies to these buildings is an example of that. The basic definition of thermal comfort from ANSI ASHRAE (1966) points out that it is a condition of mind in which someone expresses satisfaction with the thermal environment.

A building enclosure and its components should be designed to provide a comfortable and protected indoor environment. The building envelope acts as a 'filter' between the outdoor environment and the indoor space. Although the main task of the building envelope is environmental, only recently it has begun to attract due attention; Primary emphasis on the appearance, that is, the visual function of the building envelope, is a practice that is relatively common in building design (ATHIENITIST; SANTAMOURIS, 2002). When it comes to low-cost houses (LCH), which rarely count with artificial conditioning systems due to the low financial resources applied during the building and maintenance stages, the building envelope plays an important role concerning their thermal performance. As Brazilian LCH design counts with small glazing area, this research focuses on building opaque envelope (OE) thermo physical properties that affect the heat transfer between indoor and outdoor: thermal transmittance (U-value), heat capacity (HC), and solar absorptance (α). Numerous researches have been investigating these properties and their conjugated impact on thermal performance has been highlighted; also, the opaque envelope (OE) behavior has been linked to the peculiarities of each climate.

The housing scenario in Brazil demands great effort to overcome the house shortage and to provide high-quality buildings. A massive construction of low-cost houses has been occurring in Brazil to face housing shortage; since 2006 government initiatives regarding housing financing have been developed to benefit the middle and low-income people. However, this constructive impulse has gone ominously, resulting in urban and architectural designs with low quality (FERREIRA, 2012), ignoring the use of thermal comfort strategies (MONTEIRO; VELOSO; PEDRINI, 2012). Passive thermal comfort strategies, such as natural ventilation, shading devices and building envelope thermal properties specifications, are highly important in Brazilian LCH design as, due to its installation and operation costs, this kind of building rarely counts with artificial conditioning. These strategies must be defined considering each climate peculiarities; however, the current construction has been undertaken as a pattern with no cultural or climate distinguishes. Series of researches have been developed to assess thermal comfort in Brazilian LCH in different climates (CHVATAL, 2014; LUCAS et al., 2011; MARQUES, 2013; MORENO; SOUZA, 2011; SCHWONKE et al., 2011; TRIANA; LAMBERTS, 2013), highlighting the importance of specific considerations and pointing out the relevance of the conscientious building design process.

In1945 Villanova Artigas, a great icon of the Brazilian modern architecture, used a letter to a client to highlight the importance of the design process to ensure constructions quality and economic viability (FERRAZ et al., 1997), and over the years the importance of design has been reaffirmed. Certainly, the advances in building performance simulation (BPS) tools, allowing building performance to be evaluated before construction, contribute to it.

Thermal analysis BPS tools have the potential to foresee how a design alternative will respond to the outdoor temperature variation. Therefore, they may provide quantitative information to guide the building design process. Because the early design stage allows more flexibility to generate design alternatives, this is the period when the decisions have the most impact on the overall building performance. Then, if applied during the conceptual design stage the potential of such tools is increased. However, BPS tools are mainly used in final stages to analyze a single design alternative, usually for code compliance checking (HENSEN et al., 2004; HOBBS et al., 2003; HYGH et al., 2012; MORBITZER, 2003; RIZOS, 2007; STRUCK; HENSEN; KOTEK, 2009).

The underutilization of BPS during early design results, among others, from the lack of tools appropriate to this stage (HOBBS et al., 2003). According to Hygh et al. (2012) and Rizos (2007), to characterize the buildings for simulation modeling the user must provide a lot of technical specifications, and most of them are defined only when the design approaches the final stages. Due to the high complexity of BPS software, such as Energy Plus, the simulation process demands a lot of time from an expert user, increasing the design cost and contributing to the unexpressive use of these tools by the design team (WESTPHAL, 2007). Therefore, it is still inaccessible in designs that count with low financial investment, as the LCH (MARQUES; CHVATAL, 2011).

Due to the benefits that may result from implementing BPS during early design, efforts have been made to overcome the barriers that stand against it. The developments of simplified BPS tools, that are able to provide accurate predictions, are an important step toward the promotion of early design conscientious decision-making guided by quantitative information. The scientific literature has frequently indicated that regression-based statistical techniques may be used as an option to create simplified and accurate models to quickly assess the building performance (CARLO; LAMBERTS, 2008; CATALINA; IORDACHE; CARACALEANU, 2013; CATALINA; VIRGONE; BLANCO, 2008; EISENHOWER et al., 2012; HYGH et al., 2012; KOROLIJA et al., 2013; LAM et al., 2010; SIGNOR; WESTPHAL; LAMBERTS, 2001; WU; SUN, 2012). Regression models can be created from a series of parametric simulation runs conducted using robust software (e.g., Energy Plus). Once obtained, the regression models may work independently of the detailed performance software and its accuracy can be statistically determined and optimized. Standard documents such as building envelope trade-off option from ANSI ASHRAE 90.1 (2007), RTQ-C (INMETRO, 2010) and RTQ-R (INMETRO, 2012) use this kind of approach to evaluate whether the final design is in accordance with some predefined quality parameters.

This research intends to improve the quality of naturally ventilated low-cost houses in Brazil by developing regression models, adapted to three Brazilian climates, to predict building thermal discomfort in a fast, simple and accurate manner for use in the early design stages. These models are created using regression analysis based on a large set of detailed performance model simulation runs.

2. OBJECTIVES

General:

- To develop regression models for thermal discomfort prediction in naturally ventilated low-cost houses, within three Brazilian climates, during the early design stage.

Specific:

To contribute with the assessment of the opaque envelope thermo-physical properties conjugated impact on the thermal discomfort in Brazilian low-cost houses;

- To develop a method for creating regression equations focused on predicting thermal discomfort on naturally ventilated Brazilian low-cost houses.

3. LITERATURE REVIEW

3.1. THERMAL COMFORT AND BUILDING ENVELOPE IN LOW-COST HOUSES

3.1.1. BASIC CONCEPTS

According to the Brazilian building energy efficiency regulation (Energy efficiency technical requisites for residential building performance - INMETRO 2012) the building envelope is defined by a set of planes that configure a boundary between outdoor and indoor environment such as facades, gables, roofing, openings and other elements with the exception of the floor. The building envelope combines two classes of elements: transparent (windows, glazed areas, openings, etc.); and opaque (walls, slabs, roofs, etc.). The building envelope can be considered as a 'filter' that intermediates the heat transfer among others interactions between indoor and outdoor space. When considering low-cost houses (LCH), which have small area of transparent elements, the building opaque envelope (OE) shows major impact on thermal comfort allowing numerous design strategies exploration.

"Heat transfer (or heat) is energy in transit due to a temperature difference" (INCROPERA; DEWITT, p2, 1996). The heat transfer between the indoor and outdoor environments occurs as a consequence of a temperature gradient, and its flux goes from the higher to lower temperature medium (id. ibid). To control the temperature of a specific space the mechanism by which heat is gained and lost must be understood and, as far as possible, quantified (HALL; ALLINSON, 2010).

Thermal transmittance (U-value), heat capacity (HC) and solar absorptance (α) are highly important building OE parameters that affect the heat transfer. A set of performance standards and regulations consider these parameters establishing design guidelines, such as the national standards NBR 15220 (ABNT, 2005), NBR 15575 (ABNT, 2013), and RTQ-R (INMETRO, 2012).

THERMAL TRANSMITTANCE (U-value)

The U-value is the inverse of the OE ambient to ambient total thermal resistance determined by equations 01 to 04 from NBR15220 (ABNT, 2005).

$$R = \frac{l}{\lambda} \qquad (Equation\ 01)$$

where:

R: homogeneous layer thermal resistance in (m2.K/W);

l: layer thickness in meter;

λ: material thermal conductivity: Physic property of a homogeneous and isotropic material, which presents a constant heat flux, with density of 1W/m2, when subjected to a uniform gradient temperature of 1 Kelvin per meter - Considered units: W/(m.K).

$$R_t = R_{se} + R_{t1} + R_{t2} + \cdots + R_{tn} + R_{air1} + R_{air2} + \cdots + R_{airn} \qquad (Equation\ 02)$$

where:

$R_{t1} + R_{t2} + \cdots + R_{tn}$: are the thermal resistance of the n homogeneous layers (m2.K/W) calculated with equation 01;

$R_{air1} + R_{air2} + \cdots + R_{airn}$: are the thermal resistance of the n air layers (m2.K/W) according to NBR 15220 (INMETRO, 2005) tabulated data.

$$R_T = R_a + R_t + R_i \qquad (Equation\ 03)$$

where:

R_t: is the surface to surface thermal resistance, defined in equation 02 (m2.K/W). This property is related to conduction heat transfer mode;

R_a and R_i: are the thermal resistances of outer and inner air film (m2.K/W). This property is related to convective and radiation heat transfer modes.

$$Uvalue = \frac{1}{R_T} \qquad (Equation\ 04)$$

where:

R_T: is the ambient to ambient total thermal resistance, defined by equation 03.

HEAT CAPACITY (HC)

HC is the Quotient of the heat quantity needed to vary the system temperature in one unit by the area of the component; it may be calculated using equation 05 (ABNT, 2005).

$$HC = \sum_{i=1}^{n} \lambda_i . R_i . c_i . \rho_i = \sum_{i=1}^{n} l_i . c_i . \rho_i \qquad (Equation\ 05)$$

where:

λ_i: is the material thermal conductivity of layer i;

R_i: is the thermal resistance of layer i;

l_i: is the layer i thickness;

c_i: is the specific heat of layer i material;

ρ_i: is the density of layer i material.

SOLAR ABSORPTANCE (α)

From the total solar energy that reaches the OE part is reflected and other is absorbed and the coefficients of reflectivity (r), and absorptance (α) rule these processes; the equation 06 indicates the relation between these properties:

$$\propto + r = 1 \qquad Equation\ 06$$

The α is calculated according to equations 07 (ABNT, 2005):

$$\propto = \frac{Solar\ radiation\ absorbed\ by\ a\ surface}{Incident\ solar\ radiation\ at\ the\ surface} \qquad Equation\ 07$$

The architectural design plays an important role concerning the building thermal performance. During early design stages designers have a great flexibility to propose and implement thermal comfort strategies. As design process approaches to the final stages just a few design parameters remain flexible, so the possibilities to solve problems are limited. Therefore, decisions taken during conceptual design generate the most significant impact on the final building performance.

The *Figure 1* illustrates the importance to make informed decisions during the early design stages, indicating the reduction in design decision effectiveness along the life of building stages.

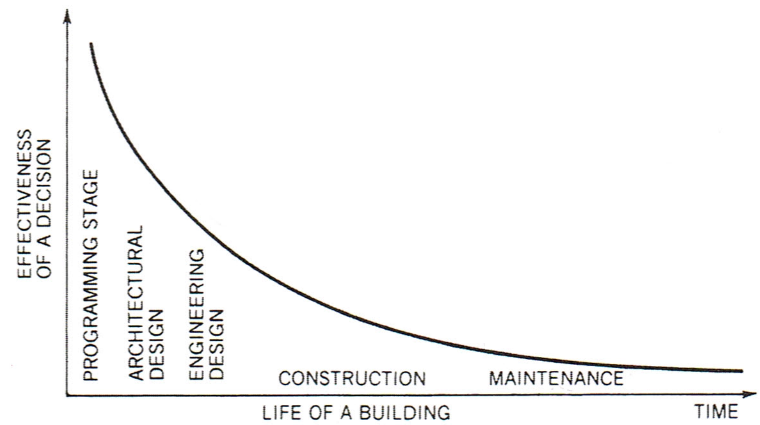


Figure 1: Effectiveness of design decision during the life of building (Source: LECHNER, 2014)**.**

The relevance of the early design stages on the final building performance highlight the importance of using quantitative information as guidance to designers. However, performance analyses are uncommon in architectural practice occurring for a few buildings that face engineering challenges or an explicitly focus on sustainability mostly after or at the final design stages (SCHLUETER; THESSELING, 2009).

Usually, architectural design decisions are based on general recommendations and qualitative information acquired from previews experiences. Although decisions based on these experiences may result in good quality buildings, the use of quantitative assessment methods greatly improves the design support, contributing with the building final performance (RAONI; PEDRINI, 2011).

To ensure the effectiveness of thermal comfort strategies their parameters must be considered since early design stages. Therefore, it is important to provide designers with thermal comfort assessment tools to guide the decision-making. In this sense, computational tools may be used to assist the design process (MARQUES; CHVATAL, 2011).

Concerning the sustainability, Gonçalves and Duarte (2006) point out the need of a design process supported by computational simulation tools. The authors indicate that to link the concepts of thermal comfort, energy efficiency and environmental issues building designers may consider, among others, (a) building wind and solar exposure; (b) internal zones; (c) environmental features; (d) and materials of the building structure and envelope – considering its colors and thermal performance. Together, these parameters have an influence on building thermal performance as they play an important role on the definition of design strategies regarding natural ventilation, shadings, reflection of the direct solar radiation, thermal inertia, and thermal insulation, etc. It is highlighted that the appropriate use of these strategies is defined accordingly to the environmental weather conditions and regulations concerning the building performance and the terrain use and occupancy.

Oral, Yener, and Bayazit (2004) indicate that to achieve visual, acoustic, and thermal comfort in building envelope design two issues may be considered: (a) the outdoor environment with parameters that cannot be controlled by designers, such as weather conditions, wind, solar radiation, humidity, etc.; and (b) the built environment, whose parameters – encompassing the scales of the territory, building, indoor environments and components – can be controlled according to the human needs. Considering thermal comfort, the authors indicate that the envelope properties such as material thickness, density, specific heat; coefficients of conductivity, absorptance and reflectivity have a great impact and their influence is also combined with parameters from the other mentioned scales.

Kumar and Suman (2013) also point out that walls and roofs heat capacity and U-value properties have a great impact on naturally ventilated buildings' indoor thermal comfort and on air-conditioned buildings' cooling loads.

Therefore, to ensure good levels of building thermal performance it is important to consider, during the design process, the local weather conditions and the thermo-physical properties of the building OE.

3.1.3. THE IMPACT OF BUILDING ENVELOPE THERMO-PHYSICAL PROPERTIES ON INDOOR THERMAL CONDITIONS

Determining the maximum building envelope U-value is a common practice among thermal performance standards and regulations of residential building performance in several countries; this concept indicates that thermal performance is always correlated to the insulation increase, which has been questioned in a series of researches.

D'Orazio, Perna and Giuseppe (2010) remark that European standards concerning building energy performance establish specific guidelines on thermal insulation to reduce winter energy consumption, while summer design strategies are described almost qualitatively. Climate differences are not considered and the building envelope insulation is regarded as the main strategy to control energy consumption. This approach encourages the use of materials and construction technologies that does not fit the traditional southern European building where the increase of insulation may negatively affect the indoor thermal conditions during the summer. Based on prototype monitoring in the Mediterranean climate – region near to Ancona, Italy – the authors point out that the insulation layer increase may reduce the effectiveness of traditional passive cooling strategies such as the attic ventilation. This behavior may be linked to the dissociation between the indoor thermal conditions and the roof external upper layer.

Chvatal and Corvacho (2009) also analyzed, through computational simulation, the impact of increasing the building envelope insulation on thermal performance of distinct building models located in Portugal and other Southern European countries. The results showed that the insulation increase does not always contribute to thermal comfort and energy efficiency and that with insulation addition the solar and internal gains must be closely controlled to avoid summer overheating. Considering Brazilian scenario Carlo and Lamberts (2008), and Roriz, Chvatal and Cavalcanti (2009) found similar results.

In climates with hot summers and cold winters, energy-efficient residential design must consider the parameters related to the heat loss during the winter, solar heat gains during the summer, and natural ventilation in transitional seasons. The heat transfer process through the building envelope differs in summer and winter, and the mass and heat transfer must be considered if natural ventilation is provided. An energy-efficient building design cannot be reached by using only one approach, such as increasing the thermal insulation (FENG, 2004).

Considering the influence of building envelope thermal insulation and other external parameters on heat transfer between indoor and outdoor environments, Assem (2011) points out the relevance of the absorptance (α) and the building façade orientation on the solar radiation absorbed by walls and roofs external surface. The author proposes, for Kuwait weather, a correlation between the maximum U-value and the solar absorptance coefficient for each building orientations (north, south, east, west, and roof). Chvatal (2014) also demonstrated the conjugated impact of U-value and solar absorptance on low-cost houses thermal comfort for winter and summer weather in three Brazilian cities (Curitiba/PR, São Paulo/SP, and Manaus/AM); highlighting that the best design alternative must be achieved balancing the winter and summer thermal needs and the combination of U-value and solar absorptance.

Cheng, Ng and Givoni (2005) analyzed the effect of building envelope color and thermal mass on the indoor thermal conditions of test cells built in the warm-humid climate of Hong Kong. The results show that the sensitivity of the envelope color on indoor thermal performance varies with thermal mass and global solar radiation - high solar radiation levels combined with lightweight building reaches more sensitivity. The use of light colors surfaces are indicated as a simple, effective and economical way to reduce indoor temperature in warm-humid climate. High mass building envelope also reduces the indoor maxima and - differently from the color effect - increases the indoor minima.

Also considering the outer envelope solar radiation absorption, Dornelles (2009) highlights that this kind of heat gain is responsible for a great amount of the building thermal loads, and its impact is primarily defined by the solar absorptance of the building envelope components. The solar absorptance data of different colors and wall paint types were obtained by reflectivity measurements. The results show that the color cannot be considered as the unique decisive parameter concerning the opaque surface absorptance. The lack of current and accurate data has been leading designers and researchers to consider visual perception and color based on tabulated data, strengthening the idea that the increase absorptance is only linked to darkening colors. The surface roughness is also explored, presenting linear relationship with the surface absorptance.

According to Balaras (1996), thermal inertia can reduce peak cooling loads and indoor temperature swings, also can be an effective alternative on energy conservation and to provide more comfortable indoor thermal conditions. The thermal inertia increases the outer envelope ability to neutralize the exterior temperature and heat flow fluctuations, and the lag time between the temperature distribution in the inner and outer surfaces (FENG, 2004).

Goulart (2007) remarks that thermal mass design strategies are frequently recommended to warm-dry; but it may also contribute to improve the building performance in warm-humid climates. The advantages and limitations of thermal inertia as a cooling passive design strategy in the warm-humid summer conditions of Florianópolis, Brazil, were explored with parametric simulations considering: (a) naturally and mechanical ventilation, (b) existence and dimensions of shading devices in the openings, (c) different roof and walls thermal mass compositions. Also, a series of correlations considering these parameters are considered: window to floor ratio, nocturnal ventilation and peak internal temperature, surface of the heat transfer exposed mass, daytime ventilation, etc. The results show that greater thermal performance levels are achieved when different design strategies are combined rather than using only thermal inertia. Also, nocturnal ventilation is extremely indicated to high mass buildings, and shading strategies are very important in regard to extensive glazed that allows high levels of solar heat gains.

These researches indicate that thermal transmittance (U-value), heat capacity (HC), and solar absorptance (α) are the building envelope properties that most impact the indoor thermal condition. The building performance is mostly a result of these properties conjugated effect, and their use as design strategies is linked to particularities of the building, as the outdoors weather condition, occupation schedules, building orientation in regard to solar radiation, ventilation strategies, etc.

3.2. OPAQUE BUILDING ENVELOPE THERMO-PHYSICAL PROPERTIES GUIDELINES ON NATIONAL STANDARDS AND TECHNICAL REGULATIONS

As previously mentioned, thermal transmittance (U-Value), solar absorptance (α), and heat capacity (HC) have a great importance on building thermal performance and national standards and regulations provide design guidance and performance assessment procedures considering these parameters.

The following sub-items show a brief explanation on how Brazilian standards and regulation consider these opaque envelope thermo-physical characteristics. Later, these documents are compared, and some questionings about it are pointed out.

3.2.1. NBR15220 – BUILDING THERMAL PERFORMANCE /"DESEMPENHO TÉRMICO DE EDIFICAÇÕES"

Published in 2005 the NBR15220 – "Building thermal performance" (ABNT, 2005) is the first national standard to address this topic. The document is divided according to the following sections:

- Part 1: Symbols and units definitions;
- Part 2: elements and building components U-value, heat capacity, time lag, and solar factor calculation methods;
- Part 3: Brazilian bioclimatic zones and single-family low-cost house building guidance;
- Part 4: Thermal resistance and thermal conductivity measurements using the guarded hot plate principle;
- Part 5: Thermal resistance and thermal conductivity measurements using flow meters method.

Parts 2 and 3 deal with the building OE focusing on single-family low-cost houses. Brazilian territory is divided into eight bioclimatic zones; *Table 1* summarizes the limit-values for the OE thermo-physical properties that are considered among the NBR 15220 building guidelines defined for each bioclimatic zones:

Table 1: Building envelope constructive guideline provided by NBR 15220 (Adapted from: ABNT, 2005).

BUILDING ENVELOPE COMPONENT		**BIOCLIMATIC ZONE**	**THERMAL TRANSMITTANCE "U-value" ($W/m^2.k$)**	**TIME LAG* "φ" (h)**	**SOLAR FACTOR ** "FSo" (%)**
WALL	Lightweight	01; 02	≤ 3.00	≤4.4	≤5.0
	Reflective lightweight	03; 05; 08	≤3.60	≤4.3	≤4.0
	High-mass	04; 06; 07	≤2.20	≤6.5	≤3.5
ROOF	Insulated lightweight	01; 02; 03; 04; 05; 06	≤2.00	≤3.3	≤6.5
	Reflective lightweight	08	≤2.30 x FT***	≤3.3	≤6.5
	High-mass	07	≤2.00	≤6.5	≤6.5

* Time lapsed, concerning periodic heat transfer, between a thermal variation in a means and its manifestation in the opposite surface of the building component.
** Quotient between the solar radiation rate transmitted through an opaque component and the total solar radiation rate incident on its external surface
*** Corrector factor of the acceptable thermal transmittance for the bioclimatic zone 8 (dimensionless) according to the equation: $FT=1.17 - 1.07 \times h^{-1.04}$, where 'h' represent the opening height in opposite eaves

3.2.2. NBR 15575: RESIDENTIAL BUILDINGS – PERFORMANCE / "*EDIFICAÇÕES HABITACIONAIS – DESEMPENHO*"

The Brazilian national standard NBR 15575 (ABNT, 2013) is focused on the users requirements and needs to residential building use. These criteria may be subdivided in three groups: (a) Security – concerning the structure, fire protection, and use during occupation; (b) Habitability - thermal, acoustic and illuminance performance, sealing, health, hygiene and air quality, functionality and accessibility, among others; And sustainability - durability; maintainability; and environmental impact. For each of these items, some guidelines and methods are provided to improve and assess the building system performance.

The NBR 15575 is divided into six sections:

- Part 01: General requirements
- Part 02: Structure system requirements
- Part03: Floor system requirements
- Part 04: External and internal wall requirements
- Part 05: Roof system requirements
- Part 06: Sanitary system requirements

The item thermal performance of Part 01, Part 04 and Part 05 addresses the opaque building envelope issue.

Regarding the building thermal performance assessment NBR15575 indicates two methods: the simplified, or normative, which singly assess wall and roof systems by using thermal properties calculations and comparisons between the component properties and the standard guidelines; and the application of building performance simulation (BPS), which is recommended if the simplified method results in unsatisfactory thermal conditions, the BPS considers the whole building as an integrated system.

Table 2 shows the guidelines proposed by this standard to residential buildings. For each Brazilian bioclimatic zones U-value and heat capacity value limits are defined

Table 2: Building envelope constructive guideline provided by NBR 15575 (Adapted from: ABNT, 2013)

<table>
<tr><th rowspan="2">BUILDING ENVELOPE COMPONENT</th><th colspan="9">NÍVEL MÍNIMO DE DESEMPENHO TÉRMICO DAS VEDAÇÕES EXTERNAS</th></tr>
<tr><th>BIOCLIMATIC ZONE</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th></tr>
<tr><td rowspan="2">WALLS</td><td>THERMAL TRANSMITTANCE “U-value” (W/m² . K)</td><td colspan="2">≤ 2,5</td><td colspan="6">≤ 3,7 se α ≤ 0,6
≤ 2,5 se α > 0,6</td></tr>
<tr><td>HEAT CAPACITY “HC” (KJ/m² . K)</td><td colspan="7">≥ 130</td><td>No requirement</td></tr>
<tr><td>ROOF</td><td>THERMAL TRANSMITTANCE “U-value” (W/m² . K)</td><td colspan="2">≤ 2,3</td><td colspan="5">≤ 2,3 if α* ≤ 0,6
≤ 1,5 if α* > 0,6</td><td>≤ 2,3 FV** if α* ≤ 0,4
≤ 1,5 FV** if α* > 0,4</td></tr>
</table>

* Solar radiation absorptance of wall and roof external surface
** Ventilation factor (FV) is defined in NBR 15220 (ABNT, 2005)

Concerning the BPS method, NBR15575 shows modeling recommendations: location and weather data for typical winter and summer day; simulation software to be used; thermal zoning (considering each room as a zone); building envelope thermo-physical properties to be considered. The performance analysis considers basic requirements regarding the upper temperatures in winter and lower temperatures in summer.

3.2.3. ENERGY EFFICIENCY TECHNICAL REQUISITES FOR RESIDENCIAL BUILDING PERFORMANCE/ '*RTQ-R REGULAMENTO TÉCNICO DA QUALIDADE PARA O NÍVEL DE EFICIÊNCIA ENERGÉTICA EM EDIFICAÇÕES RESIDENCIAIS*'

The requisites from RTQ-R (INMETRO, 2012) – launched by the National Institute of Metrology, Standardization and Industrial Quality (INMETRO) and supported by PROCEL Edifica – aims to classify the residential building according to their energy efficiency levels by specifying technical requirements and methods to assess the building envelope thermal performance, the water heating performance, and others possible bonuses.

Regarding the building envelope thermal performance, some prerequisites concerning the acceptable range of values for exterior walls and roof U-value, heat capacity, and superficial solar absorptance according to table 3 must be considered to achieve levels A and B in the performance classification. If these prerequisites are not fulfilled in the analyzed residential unit it is still possible to classify the building, but the classification level will not be higher than C.

Table 3: RTQ-R solar absorptance, U-value and heat capacity prerequisites according to the bioclimatic zone (Adapted from INMETRO, 2012)

BIOCLIMATIC ZONE	BUILDING ENVELOPE COMPONENT	SOLAR ABSORPTANCE	U-VALUE [W/(m^2K)]	HEAT CAPACITY [KJ/(m^2K)]
01 and 02	Wall	No requirement	$U \leq 2,50$	Ct ≥130
	Roof		$U \leq 2,30$	No requirement
03 to 06	Wall	$\alpha \leq 0,6$	$U \leq 3,70$	Ct ≥130
		$\alpha > 0,6$	$U \leq 2,50$	Ct ≥130
	Roof	$\alpha \leq 0,6$	$U \leq 2,30$	No requirement
		$\alpha > 0,6$	$U \leq 1,50$	
07	Wall	$\alpha \leq 0,6$	$U \leq 3,70$	Ct ≥130
		$\alpha > 0,6$	$U \leq 2,50$	Ct ≥130
	Roof	$\alpha \leq 0,4$	$U \leq 2,30$	No requirement
		$\alpha > 0,4$	$U \leq 1,50$	
08	wall	$\alpha \leq 0,6$	$U \leq 3,70$	
		$\alpha > 0,6$	$U \leq 2,50$	
	roof	$\alpha \leq 0,4$	$U \leq 2,30$	
		$\alpha > 0,4$	$U \leq 1,50$	

NOTE: In Bioclimatic Zone 08, no painted or varnished ceramic tile roof with no ceiling may comply with the requirements of this table if they fit the following requirements: (a) contain vents in at least two opposite eaves; and (b) the ventilation openings occupy the entire length of the respective walls. In these cases, depending on the total height of ventilation, the acceptable limits of heat transfer coefficient may be multiplied by the transmittance correction factor (TF) given by: ft = 1.17 - 1.07. h-1.04 (where: TF = transmittance factor acceptable to the covers of Bioclimatic Zone 8; h = height of the opening in two opposite eaves (cm)).

Beyond, two methods may be used to assess the building envelope performance: (01) a prescriptive method by applying regression models for each long stay room of an independent residential unit according to its bioclimatic zone; and (02) a simulation method with specific modeling guidelines.

3.2.4. NBR 15220, NBR15575, AND RTQ-R COMPARISON AND DISCUSSION

The presented standards and regulations certainly represent a progress on Brazilian building, but it is very important to keep the discussions to continuously improve and update them.

Some incoherencies are found in the comparison of building envelope properties among NBR15220 (ABNT, 2005), NBR15575 (ABNT, 2013), and RTQ-R (INMETRO, 2012). *Table 4* shows, for each document, the acceptable values of external wall properties: solar factor (SF), thermal transmittance (U-value), heat capacity (HC), and time lag (φ). Different U-values limits are defined between the NBR 15220 and the other regulations. In the first document the guidelines about the solar absorptance values are defined based on the solar factor, and the guidelines about the heat capacity is established by the definition of a maximum time lag for each bioclimatic zone. In the remaining documents a correlation of the surface solar absoptance and its e U-value is considered, and a minimum heat capacity limit is defined.

Table 4. Comparative of wall thermal physical properties from NBR 15220, NBR 15575, and RTQ-R (Adapted from MARQUES, 2013).

BIOCLIMATIC ZONE		1	2	3	4	5	6	7	8
Thermal transmittance “U” (W/m².K)	NBR 15220-3	U ≤ 3,0		U ≤ 3,6	U ≤ 2,2	U ≤ 3,6	U ≤ 2,2		U ≤ 3,6
	NBR 15575-4	U ≤ 2,5		U ≤ 3,7 se α ≤ 0,6 U ≤ 2,5 se α > 0,6					
	RTQ-R								
Heat Capacity “HC” (KJ/m².K)	NBR 15220-3	-							
	NBR 15575-4	Ct ≥ 130							NO REQUISITE
	RTQ-R								
Solar Factor “SF” (%)	NBR 15220-3	FS ≤ 5,0		FS ≤ 4,0	FS ≤ 3,5	FS ≤ 4,0	FS ≤ 3,5		FS ≤ 4,0
	NBR 15575-4	-							
	RTQ-R								
Time Lag “φ” (h)	NBR 15220-3	φ ≤ 4,3			φ ≥ 6,5	φ ≤ 4,3	φ ≥ 6,5		φ ≤ 4,3
	NBR 15575-4	-							
	RTQ-R								

Table 5 shows a comparison between Brazilian standard and regulation guidelines for the roof properties. Similar to *Table 4*, the U-value limits from the NBR 15220 is different from the value indicated by the other documents, and the color considerations also remains the same.

Table 5. Comparative of wall thermal performance strategies from NBR 15220, NBR 15575, and RTQ-R (Adapted from MARQUES, 2013).

BIOCLIMATIC ZONE		1	2	3	4	5	6	7	8
Thermal Transmittance " (W/m².K)	NBR 15220-3	U ≤ 2,0							U ≤ 2,3 FT
	NBR 15575-4	U ≤ 2,3		U ≤ 2,3 se α ≤ 0,6 U ≤ 1,5 se α > 0,6				U ≤ 2,3 FV se α ≤ 0,4 U ≤ 1,5 FV se α > 0,4	
	RTQ-R								
Solar Factor "SF" (%)	NBR 15220-3	FS ≤ 6,5							
	NBR 15575-4	-							
	RTQ-R								
Time lag "φ" (h)	NBR 15220-3	φ ≤ 3,3						φ ≤ 6,5	φ ≤ 3,3
	NBR 15575-4	-							
	RTQ-R								

Researchers have also been investigating incoherencies between the performances evaluations proposed in these documents. Loura, Assis and Bastos (2011) compared the results from NBR15575 (ABNT 2013) and RTQ-R (INMETRO 2012) assessment methods for a multi-family building in Rio de Janeiro. Using the RTQ-R the building received grade B for energy-efficiency classification, while with the NBR15575 assessment method the same building did not achieved the minimum acceptable performance. Brito et al. (2012), Marques and Chvatal (2013), and Chvatal (2014) indicated inconsistent results between NBR 15575 normative and simulation assessment methods. For the same standard Sorgato et al. (2012) points out some gaps and indicated possible solutions.

3.3. BUILDING THERMAL PERFORMANCE PREDICTIVE MODELS

3.3.1. INTEGRATING BUILDING PERFORMANCE SIMULATION INTO DESIGN PROCESS: CHALLENNGES AND OPPORTUNITIES

Although several building performance simulation (BPS) tools have been developed in recent decade and this disciplinary field has reached a high degree of maturity, its use as guidance to daily design process is still unexpressive and mostly under-exploited.

To deal with the physical phenomena complexity that describes the building thermal behavior the BPS tool user must have a multidisciplinary knowledge and a wide range of constructive information to setup the virtual model for simulation. The need of such specialized users may restrict BPS to universities and research centers due to the lack of other institutions that are able to assemble professional experts from different knowledge fields (WESTPHAL, 2007).

Computational performance-based building design cope with the conflict of providing building performance feed back during early design. This is due because many design aspects are typically detailed in the later stages and significantly affect the building performance. This conflict points out the challenge of developing new methodologies to allow the use of BPS since the early design stages (BRAHME et al., 2001).

Contemporary simulation programs may provide a good array of performance assessments; However, their routine application in design practice is subject to many barrier primarily concerning the areas of quality assurance, task sharing during the program development, interoperability between computational programs, and the fact that it is mainly applied to the final stages of building design process (HENSEN et al., 2004).

To simplify and promote the building performance assessment throughout the building design process, especially in early design stages, some reduced models may be applied. These models may be developed with statistic methods based on a set of data from in situ measurements or robust simulation procedures; and its accuracy with regard to the 'original' data collector or predictor may be statistically checked. Such models may allow fast and accurate assessment of the building performance providing quantitative information to lead designers to the most efficient design alternatives.

3.3.2. THE USE OF REGRESSION META-MODELS TO ASSESS BUILDING PERFORMANCE DURING THE EARLY DESIGN STAGES

A model is an entity that represents other entity; this is an abstract and reduced representation that focuses only in some of the entity's features, in a way that it can be used to effectively understand, explore, document, and predict some behaviors and properties of the modeled entity (MAHDAVI, 2004). Therefore, BPS tools are models that predict and represent which would be the thermal and energetic behavior of a building in response to a set of physical phenomena as the heat exchange.

Cui et al. (2015) categorized the models in three groups: physics-based modeling, data-driven modeling and the hybrid of both. *Physics-based modeling*, or white box modeling, is complex and precisely compute detailed tasks and the overall real performance based on fundamental physics; a set of expert tools such as TRNSYS (KLEIN, 1990), Virtual Environment (IES, 2015), and EnergyPlus (EERE, 2014a) use physical calculation methods to generate their models. The necessary information input to run expert simulations, and the knowledge needed to perform and interpret the simulation results are highly extensive (SCHLUETER; THESSELING, 2009). *Data-driven modeling*, or black box modeling, is developed based on experimental data and statistical methods; these models count with much simpler input-output (KRISTENSEN; MADSEN; JØRGENSEN, 2004). Models based on statistic calculation applies empirically found factors instead of physical processes calculations to generate simplified models that are able to assess the building performance; Compared to the input data required in physical models, a fewer detailed information is needed for the calculation, which facilitates the parameter input. Concerning the computational time the statistic models speed up the performance assessment (SCHLUETER; THESSELING, 2009). The *physics-based and data driven hybrid modeling*, or gray box modeling, is developed with physics-based model data and the use of statistical tools. “This way models can be developed, which have almost the same validity range as white-box models, but it can be done in a less time-consuming manner and the models are guaranteed not to be overly complex” (KRISTENSEN; MADSEN; JØRGENSEN, 2004, p. 1432). Therefore, this hybrid modeling generates a *meta-model* that is a simplified statistical model to represent a physics-base model.

Numerous researches have been developing meta-models with Fourier series, neural network and regression analysis. This latter statistical analysis is widely used to describe the variation of a depended variable ‘y’ to explanatory variables ‘x_1’, ‘x_2’, x_n that are the inputs of the function. It aims to find an appropriate mathematical model by determining the best fit of model’s coefficients to explain a given data. The regression technique is a good alternative in the development of a predictive model as the output variable spans a continuous value range and the influence of the inputs on the outputs is known (CATALINA; IORDACHE; CARACALEANU, 2013).

The regression model’s performance prediction capability is restrict to the set of parameters considered for its development, e.g. the climate patterns, building type, building geometry, building materials, and human occupation patterns. Such restrictions highlight the importance of the parameter correct characterization to meet the demands that motivate its development. The use of regression analysis to generate performance predictive models is recurrently indicated in scientific literature; among these researches some are presented below.

Using multivariate linear regression, Signor, Westphal, and Lamberts (2001) developed some energy use predictive models focused on artificial conditioned office buildings within fourteen Brazilian cities. The annual consumption was correlated to design and constructive parameters that were selected according to sensibility analysis results: (a) Roof to total building envelope area ratio; (b) Window to wall ratio; (c) Shading factor; (d) glazing shading coefficient; (e) Roof's U-value; (f) Roof's absorptance; (g) Facades' U-value; (h) Facades' absorptance; (i) Internal loads. The regression was performed based on the outputs of simulation runs; the simulation setup considered two different values for each parameter – except for the facades' U-value, which was considered as a fixed value. The regression equation showed good accuracy with R^2 superior to 0.99 [1] to the most climates.

To provide quantitative information to guide designers during the early design stages Catalina, Virgone, and Blanco (2008) developed regression models to predict the monthly heating energy consumption of single-family houses in the temperate climate of sixteen cities in France. The regressions were performed from an extensive data set of performance simulation results on which the following parameters were considered: building shape; building envelope U-value; window to floor area ratio; building time constant; and a climate coefficient. The resultant regression equations showed the maximum deviation of 5,1% from the predicted to the simulated, which demonstrate that it may be used as a predictive model.

Eisenhower et al.(2012) also utilized regression techniques in the development of a meta-model to optimize the building thermal comfort and energy consumption. Uncertainty and sensitivity analysis were performed to determine the influent design parameters, and the model showed accurate prediction.

Concerning Brazilian buildings, regression equations were used to classify energy efficiency in the Energy Efficiency Technical Requisites for Residential and Commercial Building Performance – RTQ-R (INMETRO, 2012) and RTQ-C (INMETRO, 2010) respectively.

Hygh et al. (2012) used Monte Carlo [2] simulations and regression analysis to create a multivariate linear meta-model. Twenty-seven design parameters were varied in the simulations: (1) Total building area; (2) Number of stories; (3) Depth; (4) Aspect ratio; (5) Orientation; (6) Roof thermal resistance; (7) Roof color; (8) Roof emissivity; (9 – 12) Window U-value (in facades N, S, E, W); (13 - 16) Window solar heat gain coefficient (in facades N, S, E, W); (17 – 20) Wall U-value (in facades N, S, E, W); (20 – 23) Shading projection factor (in facades N, S, E, W); (24 – 27) Window-to-wall ratio (in facades N, S, E, W). The authors modeled a medium size rectangular office building in EnergyPlus considering three cities of

[1] The coefficient of determination (R^2) indicates "the portion of the variance in the dependent variable that is predictable from the independent variable (...) An R^2 of 0 means that the dependent variable cannot be predicted from the independent variable; An R^2 of 1 means the dependent variable can be predicted without error from the independent variable; An R^2 between 0 and 1 indicates the extent to which the dependent variable is predictable. An R^2 of 0.10 means that 10 percent of the variance in Y is predictable from X; an R^2 of 0.20 means that 20 percent is predictable; and so on" (STATTREK, [s.d.]).

[2] The Monte Carlo method considers a random sampling of a probabilistic distribution (DONATELLI; KONRATH, 2005). This method may be used to deal with climatic Degelman (DEGELMAN, 2004).

different bioclimatic zones in the United States. The meta-models showed good prediction accuracy compared to the simulation results. For each analyzed climate standardized regression coefficients were presented, which allowed the classification of the most sensitive parameters in early design.

Other authors have also been applying regression analysis to a set of performance simulation results to generate predictive models e.g. Nielsen (2005), Lam et. al., (2010), Wu; Sun (2012), Catalina, Iordoche, and Caracaleanu (2013), Korolija et al.(2013), etc. Most part of these predictive models has been developed to concern the building heating and cooling energy consumption and they all show good prediction fit between the regression and the robust simulations used as its base.

Therefore, regression models may be used as simplified prediction tools to assess building performance since the early design stages; and they show good accuracy.

3.4. ANSI ASHRAE STANDARD 55 - ADAPTIVE MODEL AND DEGREE-HOUS OF DISCOMFORT

ANSI ASHRAE STANDARD 55 - ADAPTIVE MODEL

The ANSI ASHRAE Standard 55 – "Thermal environmental conditions for human occupancy" has the purpose "to specify the combinations of indoor thermal environmental factors and personal factors that will produce thermal environmental conditions acceptable to a majority of the occupants within the space" (ANSI/ASHRAE, 2013, p. 2). In section 5.4 – "Determining Acceptable Thermal Conditions in Occupant-Controlled Naturally Conditioned Spaces" this standard describes the Adaptive model calculation method "that relates indoor design temperatures or acceptable temperature ranges to outdoor meteorological or climatological parameters" (id. ibid.).

According to this standard, the adaptive model's applicability is valid for occupant-controlled naturally conditioned spaces that meet four criteria:

a) Neither mechanical cooling system installed nor heating system in operation;
b) The metabolic rates of the representative occupants ranges from 1.0 to 1.3 met;
c) The representative occupants can adapt their clothing within a range at least as wide as 0.5 to 1.0 clo.
d) The prevailing mean outdoor temperature is between 10°C and 33.5°C.

A comfort range with at least 80% of acceptance is determined based on simple arithmetic means of the daily outdoor air temperatures of 7 to 30 sequential days prior to the day in question. The upper and lower for 80% acceptability limits are calculated according equations 07 and 08 from ANSI ASHRAE Standard 55 (2013).

$$Upper\ 80\%\ acceptability\ limit\ (°C) = 0.31\ \overline{t_{pma(out)}} + 21.3 \qquad Equation\ 07$$

$$Lower\ 80\%\ acceptability\ limit\ (°C) = 0.31\ \overline{t_{pma(out)}} + 14.3 \qquad Equation\ 08$$

where:

$t_{pma(out)}$: is the simple arithmetic means of the daily outdoor air temperatures of 7 to 30 sequential days

Figure 2 illustrates the acceptable temperature ranges for naturally conditioned spaces according to the adaptive method.

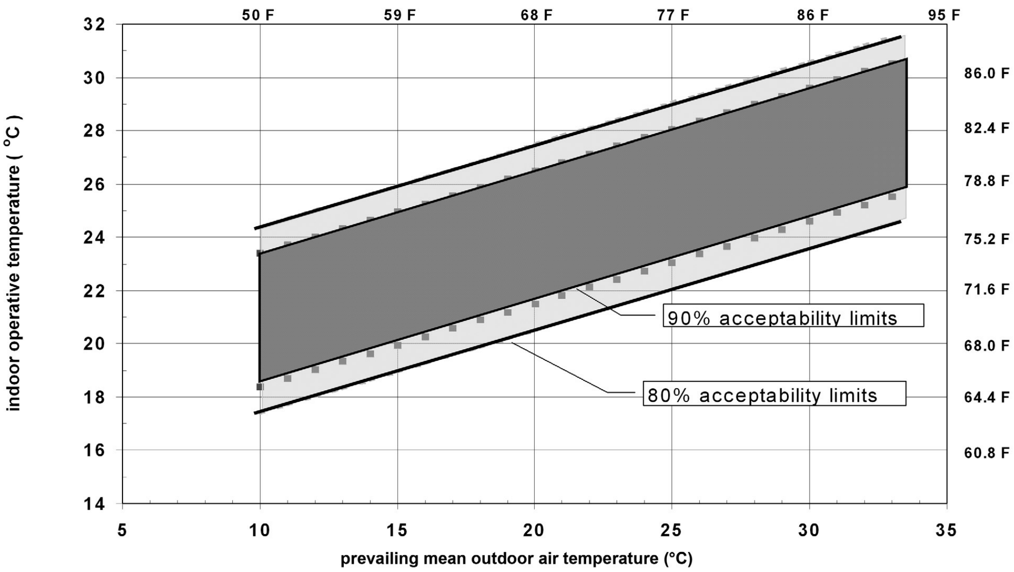


***Figure 2. Acceptable operative temperature (to) ranges for naturally conditioned spaces. Source: ASHRAE Standard 55* (ANSI/ASHRAE, 2013)**

DEGREE-HOURS (°Ch) OF DISCOMFORT

The degree-hours of discomfort is a method commonly used to quantify building thermal discomfort; the scientific literature has been registering numerous researches using this method (COSKUN, 2010; HERNÁNDEZ et al., 2014; OKTAY; COSKUN; DINCER, 2011;

PAPAKOSTAS; KYRIAKIS, 2005; RORIZ; CHVATAL; CAVALCANTI, 2009; SATMAN; YALCINKAYA, 1999; YU et al., 2011).

Figure 3 illustrates the use of this method to compute the heat and cold discomfort based on upper and lower temperature limits. When the temperature exceeds such limits the number of degree-hours of discomfort is computed.

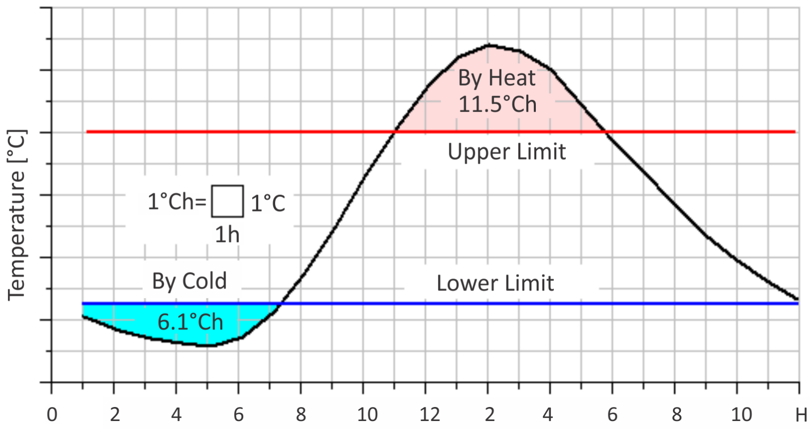


Figure 3: Degree-hours of discomfort calculation example. **(Source: RORIZ; CHVATAL; CAVALCANTI, 2009)**

The heat and cold degree-hours of discomfort during a year is calculated with equations 08 and 09 (Adapted from SILVA; ALMEIDA; GHISI, 2015):

$$DH_H = \sum_{i=1}^{8760} \{if\ OpT_i > UpL \mid (UpL - OpT_i)\ if\ OpT_i < UpL \mid 0 \qquad Equation\ 08$$

$$DH_C = \sum_{i=1}^{8760} \{if\ OpT_i < LwL \mid (LwL - OpT_i)\ if\ OpT_i > LwL \mid 0 \qquad Equation\ 09$$

where:

DH_H = Degree-hours of discomfort by heat during a year

DH_C = Degree-hours of discomfort by cold during a year

OpT_i = hourly operative temperature inside a building

UpL = upper 80% acceptability limit according to ASHRAE – 55 (ANSI/ASHRAE, 2013)

LwL = lower 80% acceptability limit according to ASHRAE – 55 (ANSI/ASHRAE, 2013)

4. METHOD

The research method encompasses the use of regression analysis to develop a set of meta-models to predict the thermal discomfort in Brazilian low-cost houses within three climates. The meta-models can be used as tools to provide decision support to designers by allowing a rapid feedback about the influence of the early design decisions on building's thermal performance.

Figure 4 shows an overview of the method developed in this research, which is subdivided into three steps: (1) Design Problem Definition, (2) Monte Carlo simulation and (3) Multivariate regression.

Multivariate regressions are performed based on an extensive data set from EnergyPlus simulation runs; the parameter combinations to be simulated are sampled with a Monte Carlo framework. To define the design space to be explored a *base model* is created and key design parameters variation ranges are determined. The Base Model deals with the characterization of the building in EnergyPlus; it encompasses the fixed parameters that characterize the building and the input data method to be used for the fixed and variable parameters. Because the meta-model prediction capability is restricted to the parameters considered during its development, the base model definition assumes a highly important role. As the objective of this research is to provide designers with quantitative information during the early design stages, the base model must assume some simplifications that provide more flexibility to the model; Therefore, benchmark tests are performed to ensure that these simplifications does not imply in any loose of accuracy, such as the thermal zone and material input methods. According to the Brazilian low-cost housing constructive practice, a group of parameters with great impact on thermal comfort is subjected to value variation in the performance simulation; the parameters and their variations are described as Design Parameters Ranges.

The Monte Carlo simulation consists in sampling the design parameters range creating a representative combination of the variable parameters. The combinations of design parameters values are substituted in an IDF base to generate the IDF(s) to run the EnergyPlus simulation. The regression analysis to develop the meta-model are based on the parameters domain, which are the values attributed to each variable parameter in the IDF(s), and the performance metric calculated from the EnergyPlus outputs.

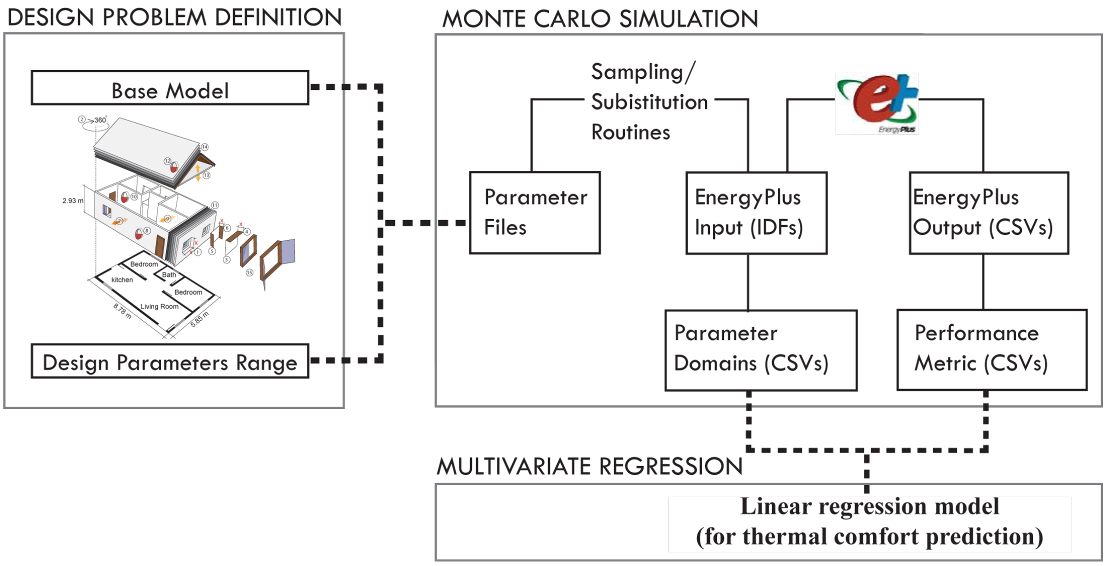


Figure 4: Method overview

4.1. DESIGN PROBLEM DEFINITION

The first step defines the design space to be explored. It is subdivided in two tasks: (a) the creation of a base model that represents the building type, which is the modeling approach and its fixed parameters, and (b) the definition of value ranges to be parametrically applied to investigate the impact of key design parameter on building thermal performance during early design. The following items show a detailed description of these tasks:

4.1.1. BASE MODEL

Because the thermal performance is sensitive, among others, to the building geometry, patterns of human occupation, use of equipment, light schedules, and building type; the base model must assume some specific definitions to characterize the design space to be explored. Among others, the floor plan dimension and distribution, thermal zooning, and building envelope system underlies the geometric modeling in this research. Therefore, a base model is created from: (a) a set of Brazilian low-cost house design projects, (b) information obtained from Brazilian standards and regulations concerning the thermal comfort of residential building, (c) weather data from 04 locations, and (d) the researchers previous acknowledgment about low-cost housing and performance modeling. The base model is created using EnergyPlus (EERE, 2014a) and a set of benchmark tests are performed to define the modeling approach that better fits this research purpose.

4.1.1.1. LOCATIONS

Three cities are considered in this research; as illustrated in Figure 5, they are located in different Brazilian geographic regions and bioclimatic zones defined according to NBR 15220 (ABNT, 2005), spanning part of the country climate diversity. The EnergyPlus weather data (EPW files) for simulations are from Roriz (2012).

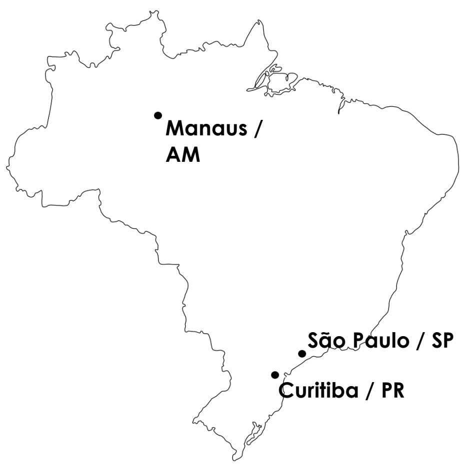


Figure 5: Location of the considered cities in Brazil

CURITIBA, PARANÁ

Located in the South Region and integrating the Brazilian Bioclimatic Zone 1 this climate spans the coldest Brazilian climates. The hourly temperature and relative humidity along the year is illustrated in *Figure* 6.

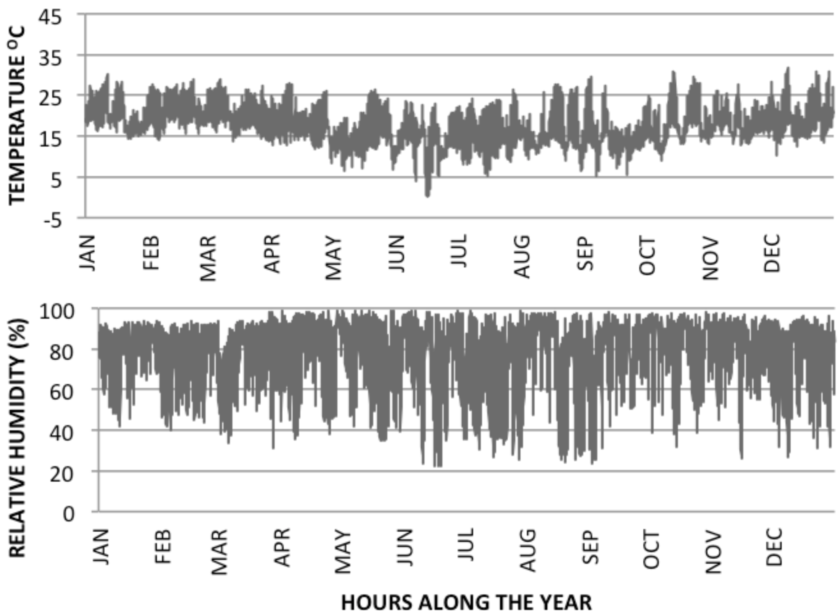


Figure 6: Curitiba/PR hourly temperature and relative humidity during a year based on EPW data file from RORIZ, 2012

SÃO PAULO, SÃO PAULO

Located in the Southeast Region and integrating the Brazilian Bioclimatic Zone 3 this climate may be considered as intermediate. The hourly temperature and average relative along the year is illustrated in *Figure 7*.

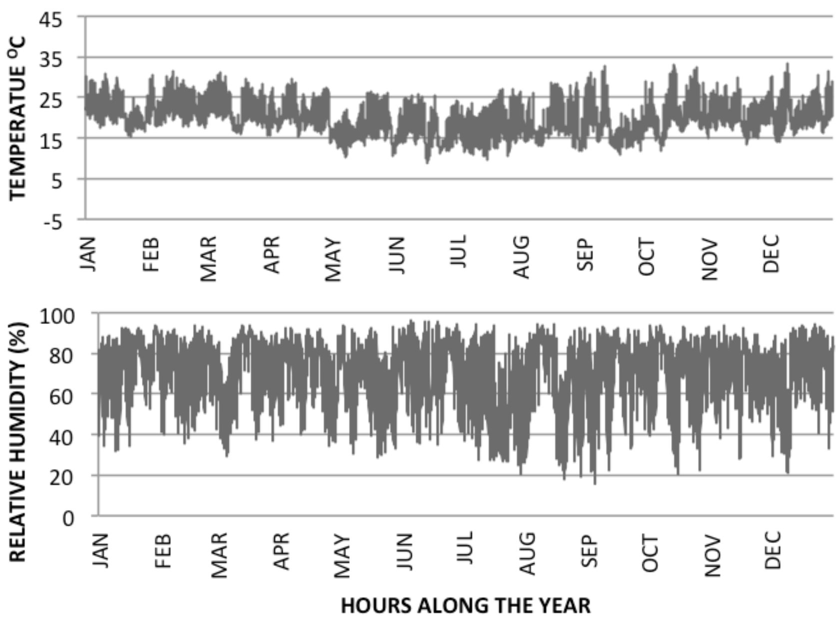


Figure 7: São Paulo/ SP hourly temperature and relative humidity during a year based on EPW data file from RORIZ (2012)

MANAUS, AMAZONAS

Located in the North Region and integrating the Brazilian Bioclimatic Zone 8 this climate is predominantly warm and humid. The annual average relative humidity is around 80% and the hourly temperature along the year is illustrated in *Figure 8*.

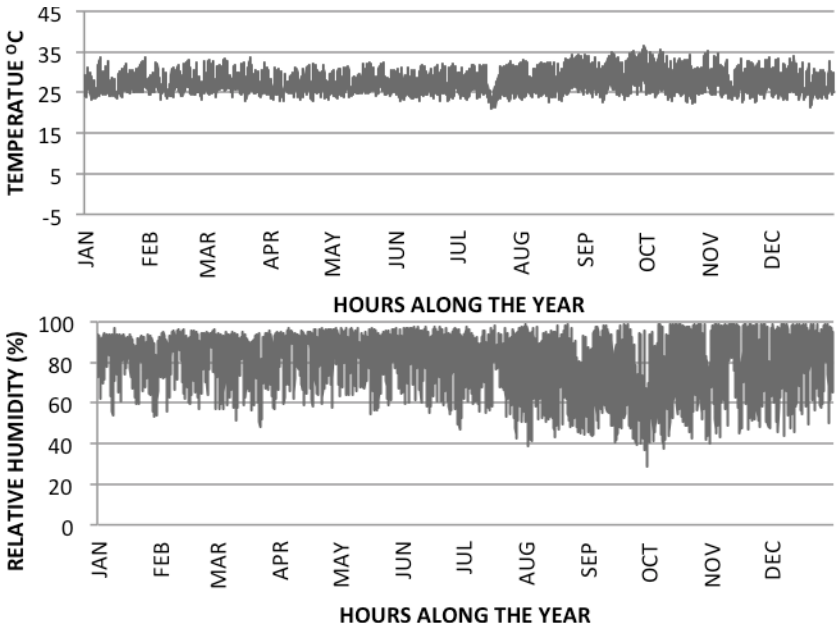


Figure 8: Manaus/AM hourly temperature and relative humidity during a year based on EPW data file from RORIZ (2012)

4.1.1.2. GEOMETRY DEFINITION

The geometric definition is based on a set of Brazilian low-cost housing design data collected within the locations considered in this research by contacting municipal institutions and financing agencies.

The geometry, constructive system and openings of the collected data are classified according to the following criteria:

Geometry

- Building type
- Number of storeys (for multi-storey building type)
- Number of bedrooms
- Attic occurrence
- Ceiling High
- Eaves and shading devices occurrence
- Frontal to side facades length ratio
- Floor plan area

Constructive System

- Roof system
- Exterior wall system
- Interior wall system
- Building envelope (exterior walls and roof) color

Openings

- Window location
- Number of facades with windows
- Window type
- Window to wall ratio (WWR)
- Window opening area

The collected and classified data is analyzed and compared; the design alternatives are discussed and used to create the model geometry (Figure 9) which is a rectangular-shaped detached unit, divided into a combined living room and kitchen, two bedrooms, a bathroom and a non-ventilated attic; counting around 50m^2 of total area. Except for the bathroom and kitchen windows the floor plan only indicates the window location, because its width will vary according to the WWR variations, which occur independently for each window.

Table 6 indicates the windows dimensions, the sill height and the percentage of its area that effectively allows natural ventilation to occur.

Table 6: Windows dimensions and effective ventilation area

ROOM	DIMENSIONS | SILL HEIGHT (m)	EFFECTIVE VENTILATION AREA (% of the window area)
Bathroom	0.6 X 0.6 |1.50	100
Kitchen	1.0 x 1.0 | 1.10	50
Bedroom 01	Vary as a function of the window to wall ratio - wwr (range: 10-90%)	Variable range: 50 to 100
Bedroom 02		
Living room		

The doors dimensions are described in *Table 7*.

Table 7. Doors dimensions

ROOM	DIMENSIONS (m)
Living room	0.8 x 2.10
Kitchen	
Bedrooms (01 and 02)	
Bathroom	0.7 x 2.10

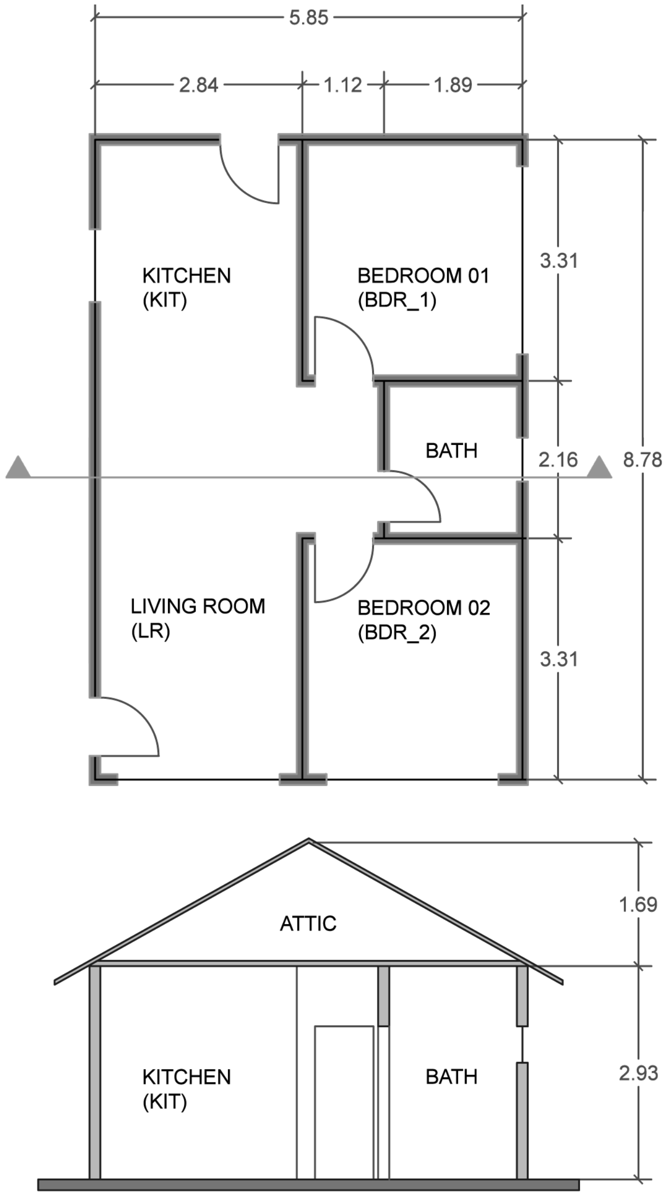


Figure 9: Model floor plan and section

4.1.1.3. INTERNAL GAINS

The lightning and electric equipment loads, the user metabolic rate, and the human occupation and lightning schedules are based on the Brazilian Energy Efficiency Technical Requirements for Residential Building Performance (INMETRO, 2012).

Figure 10 and *Figure 11* illustrate the human occupation for week and weekend days respectively. It is indicated in percentage of the total occupants for each long stay room. For each bedroom 2 people are considered; concerning the defined geometry (Figure 9), which counts with two bedrooms, the total occupation is 4 people.

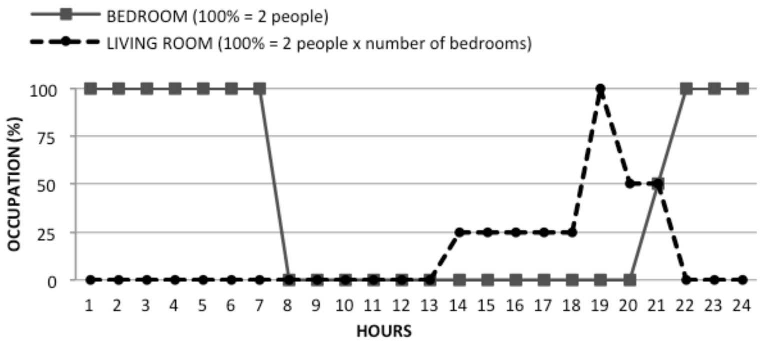


Figure 10: Human occupation schedule for week days (Adapted from INMETRO, 2012).

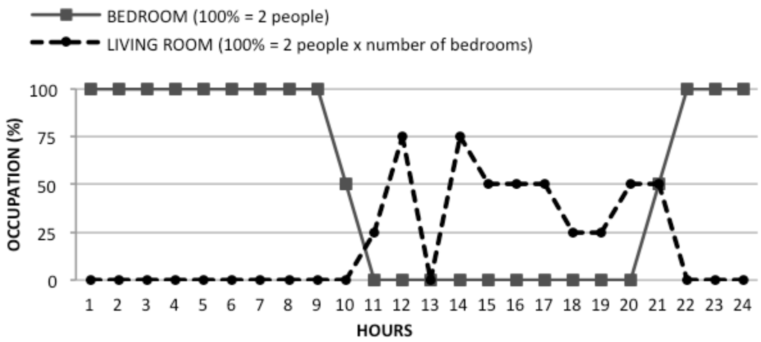


Figure 11: Human occupation schedule for weekend days (Adapted from INMETRO, 2012).

Figure 12 and *Figure 13* indicate the schedule of artificial illumination for the long-stay rooms, while *Table 8* indicates the lighting power density installed in the same rooms

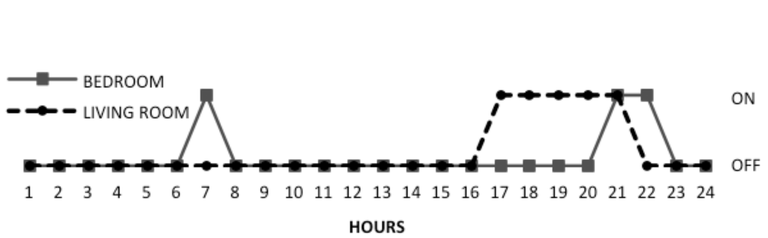


Figure 12: Lighting use in week days (Adapted from INMETRO, 2012)

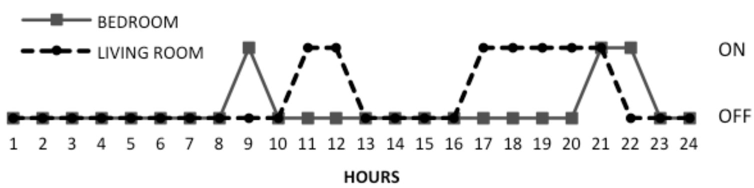


Figure 13: Lighting use in weekend days (Adapted from INMETRO, 2012)

Table 8: Lighting power density installed (Adapted from INMETRO, 2012)

ROOM	POWER DENSITY INSTALED (W/m2)
Living room	6
Bedroom	5

The internal loads from the occupants' metabolic rate and from the electric equipment installed are described, respectively, in *Table* 9 and *Table 10*.

Table 9: Human metabolic rate (Adapted from INMETRO, 2012)

ROOM	ACTIVITY	HEAT (W/m^2)	HEAT CONSIDERING THE SKIN AREA = $1.80m^2$
Living room	Sitting or watching TV	60	108
Bedroom	Sleeping or resting	45	81

Table 10: Internal loads from electric equipment (Adapted from INMETRO, 2012).

ROOM	PERIOD (hours)	POWER (W/m2)
Living room	24	1,5

4.1.1.4. VENTILATION SETUP

The natural ventilation is simulated using the EnergyPlus group: Natural Ventilation and Duct Leakage (Airflow Network). Because the building geometry assumes a rectangular form the average wind pressure coefficients, provided by EnergyPlus database were considered.

The ventilation control was defined based on temperature, by the following three requirements that must be met for natural ventilation to occur:

- Zone temperature> Set point temperature
- Zone temperature >Outdoor temperature
- The schedule must allow the ventilation; and it is setup to allow ventilation from 7 a.m. to 10 p.m. all year round.

The set-point temperature was defined as the comfort temperatures calculated for each climate according to the Adaptive Comfort Index ASHRAE-Standard 55 (ANSI/ASHRAE, 2013). The long-stay rooms effective area for ventilation is varied in the simulations according to *Table 17*.

4.1.1.5. GROUND TEMPERATURE

Due to the lack of national research that indicates values for this parameter, the ground temperature is considered as the monthly average air temperature with a correction to fit the values to the EnergyPlus limits range of 15°C to 25°C (Table 11).

Table 11: Ground Temperatures

CURITIBA/PR		
MONTH	TEMPETATURE (°C)	GROUND TEMPERATURE (°C) (Range: 15° - 25° C)
January	19.6	19.6
February	20.9	20.9
March	19.9	19.9
April	17.9	17.9
May	15.0	15.0
June	13.6	15.0
July	15.4	15.4
August	15.7	15.7
September	14.6	15.0
October	17.6	17.6
November	18.0	18.0
December	19.4	19.4
SÃO PAULO/SP		
MONTH	TEMPETATURE (°C)	GROUND TEMPERATURE (°C) (Range: 15° - 25° C)
January	21.2	21.2
February	22.3	22.3
March	21.7	21.7
April	20.8	20.8
May	17.5	17.5
June	16.8	16.8
July	17.3	17.3
August	18.3	18.3
September	17.7	17.7
October	20.5	20.5
November	20.1	20.1
December	20.9	20.9
MANAUS/AM		
MONTH	TEMPETATURE (°C)	GROUND TEMPERATURE (°C) (Range: 15° - 25° C)
January	26.8	25
February	26.8	25
March	27.6	25
April	26.4	25
May	27.0	25
June	26.8	25
July	26.7	25
August	27.9	25
September	29.0	25
October	28.2	25
November	27.3	25
December	26.7	25

4.1.1.6. SHADING DEVICES

Three types of external shading devices are considered in the base model, two are variable and one is fixed: window fins, window overhangs (both variable), and eaves (fixed).

The window fin is a stripe placed along the window left and right vertical edge; and the window overhang is a stripe placed along the window upper horizontal edge. Both are placed at 90° from the wall, with a constant material, and their size varie as a percentage of the window height. Also, 0.5m projecting eaves are fixed along all facades because it is a common practice in Brazilian LHC and show impact on the thermal performance (CHVATAL; MARQUES, 2015). *Figure 14* illustrates the mentioned shading devices.

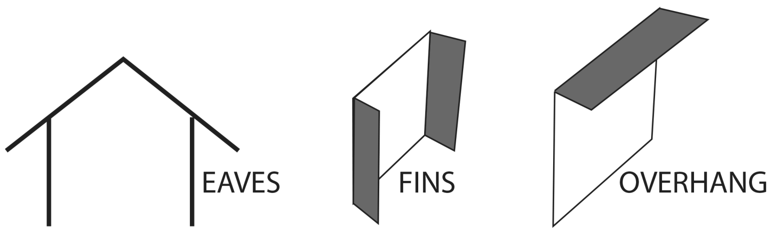


Figure 14: illustration of shading devices

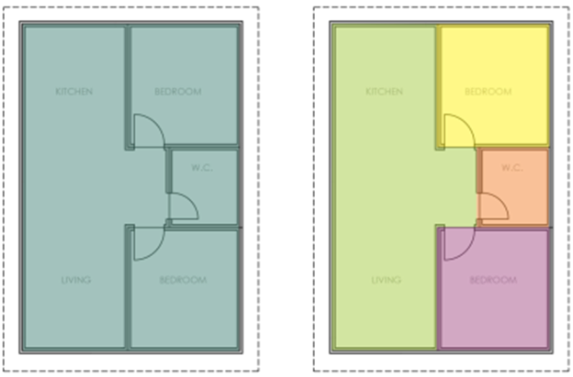
4.1.1.7. THERMAL ZONE INPUT METHOD

The zone modeling is based on thermal considerations. The zone is described as "an air volume at a uniform temperature plus all the heat transfer and heat storage surfaces bounding or inside of that air volume" (EERE, 2014b, p. 33). In BPS tools that perform heat balance, such as EnergyPlus (EERE, 2014a), the first modeling step is to divide the building into the most reduced number of zones without significantly compromising the simulation's accuracy. Determining the suitable number of zones is a challenge and the general rule is to consider the number of fans and radiant systems (EERE, 2014b, p. 33). However, there is no specific rule when it comes to naturally ventilated buildings, which does not include thermostats and artificial conditioning systems.

In naturally ventilated buildings the temperature is a function, among others, of their facades' solar insolation, envelope material and color, glazing material distribution and area, shading devices, and operable windows. Hence, there is no evidence to discard the difference temperature between the rooms of a naturally ventilated building. Besides, Brazilian low-cost houses, as exemplified by the base model floor plan (Figure 9), counts with small floor plan area and a few partitions; Also, internal doors are usually left open, so cross ventilation is allowed to occur and the room's air exchanges may contribute to minimize the temperature difference between them.

Models with a small number of thermal zones can better represent the parameters associated with conceptual design, because the room dimensions, their layout and distribution in the floor plan are not yet defined in this design stage. Therefore, some benchmark tests are performed to verify if, considering Brazilian low-cost house as the building type, a single zone model (SZM) may accurately represent a multi-zone model (MZM).

Two simulation sets were run in EnergyPlus using different zone modeling approaches: SZM and MZM. In the SZM a single zone defines the whole floor plan (*Figure 15*a), while in the MZM individual zones are used to describe each room (*Figure 15*b). For both sets the attic was described as an independent, unconditioned thermal zone that has no air exchange with other internal zones or outdoors.



(a) b)

Figure 15. (a) Single and (b) Multi-zone modeling approach; in this scheme each color represents a thermal zone.

The performance simulations considered the model in three orientations: "a", "b", and "c" as shown in *Figure 16*.

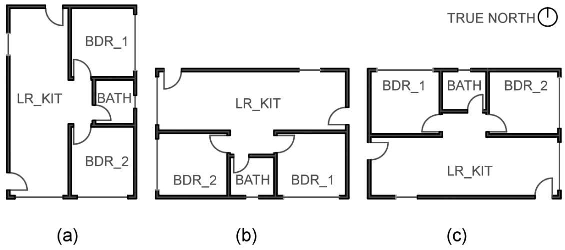


Figure 16. Building orientation scheme
Source: FAVRETTO et al., 2015

Table 12 shows an overview of the simulated cases. For all of them walls and roof system (roof and ceiling) properties are kept constant, while iterations were made between the climate and orientations.

Table 12: Overview of the analyzed cases in the zone-modeling test
Source: FAVRETTO et al., 2015

Case Number	1	2	3	4	5	6	7	8	9
Orientation	a	b	c	a	b	c	a	b	c
City	Curitiba			Manaus			São Paulo		
Wall properties	U=2.46 W/(m^2.K) | HC=150 KJ/(m^2.K) | α=0.4								
Roof properties	U=1.8 W/(m^2.K) | HC=185 KJ/(m^2.K) | α=0.7								
WWR	40% (Window-to-Wall Ratio)								

The geometry, the thermal properties of floor, doors, and glasses, the ventilation setup, and the ground temperature follow the definition shown in the previous items; and no window shading devices are modeled.

The air temperature, operative temperature, and discomfort by heat and cold predicted by the SZM are compared with the ones predicted for each long-stay room of the MZM ($\Delta = SZM_{prediction} - MZM_{ROOMprediction}$). A positive value indicates that the SZM temperature prediction overestimates the MZM's, and a negative value indicates the opposite. Considering the three metric mentioned above, the results show very small differences between the two cases, with the maximum being around -0.2°C for the air temperature (*Figure 17*a), around -0.25°C for operative temperature (*Figure 17*b), around 0.09°Ch for discomfort by heat (*Figure 18*a), and around 0.13°Ch for discomfort by cold (*Figure 18*b).

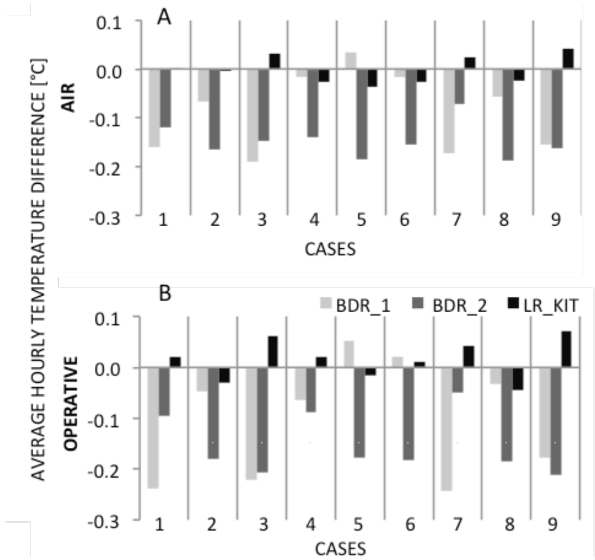


Figure 17: Annual average hourly air temperature (A) and operative temperature (B) differences between SZM and each long-stay room of MZM. Source:: FAVRETTO et al., 2015

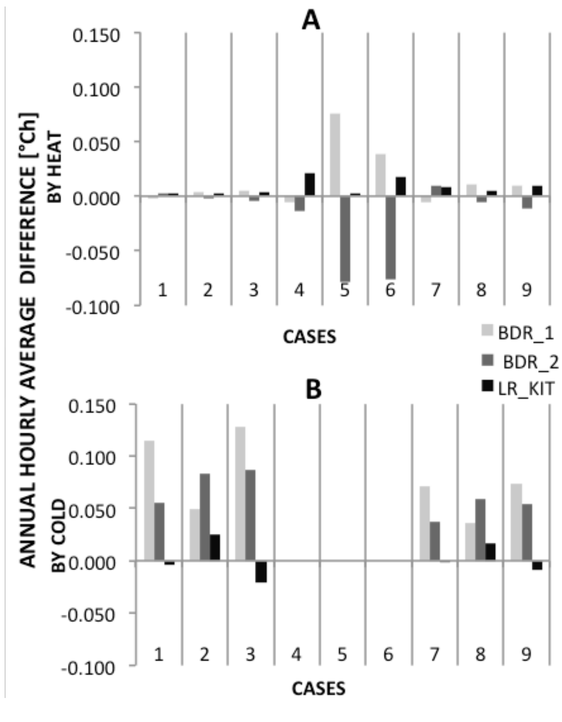


Figure 18: Annual average difference between SZM and MZM in hourly of discomfort by heat (A) and cold (B). Source:: FAVRETTO et al., 2015

Throughout the year the operative temperature difference distribution indicates that the largest share of hourly differences falls in range from 0 to 0.30°C for all analyzed cases (*Figure 19*). The same study was developed considering the other two metrics; while not presented, similar results were found.

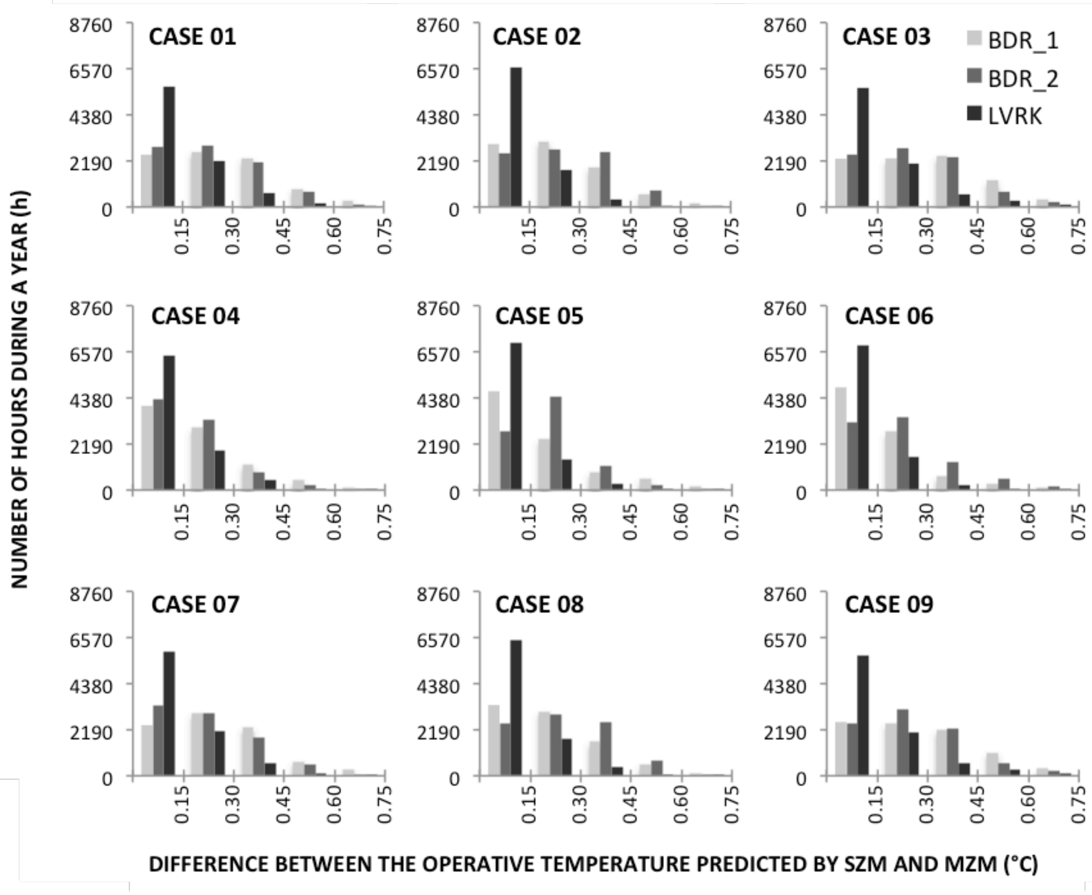


Figure 19: Distribution of hourly absolute difference between the operative temperature predicted by SZM and MZM over the course of a year.
Source:: FAVRETTO et al., 2015

From this zone modeling benchmark test, it was concluded that the SZM tends to underestimate the MZM with very low difference values, which could be considered as tolerable to represent this naturally ventilated Brazilian low-cost house. Therefore, the single zone modeling approach is considered in this research.

4.1.1.8. MATERIAL AND CONSTRUCTION INPUT METHOD

The thermal properties of internal walls, external walls and roof system (roof and ceiling) are varied in the simulations. The floor, doors and glazing properties are fixed and their thermal properties are described in *Table 13* and *Table 14*.

Table 13: Floor and doors thermal properties

Element	Layer	λ (W/m.K)	*l* (m)	*P* (kg/m³)	C (J/kg.K)	Reference
FLOOR	Crushed stone	0.7	0.030	1300	800	NBR 15220
	Concrete	1.75	0.080	2400	1000	
	Plaster	1.15	0.025	2000	1000	
	Ceramic floor tile	1.05	0.005	1600	920	
DOORS	Wood	0.12	0.035	400	1340	

λ – conductivity | *l* – thickness | *ρ* – density | C – specific heat

Table 14: Glass properties

Layer	λ (W/m.K)	*l* (m)	Solar Transmittance	Visible Transmittance	Reference
Glass	0,9	0,004	0.837	0.898	EnergyPlus library

A set of high technical specifications is required to characterize the building materials and constructions in EnergyPlus models. During the conceptual design the required information concerning the opaque envelope material thermal properties is not defined yet, as it is still a subject of investigation. Therefore, the need of a specific material properties input may reduce the potential of BPS to guide designers during early design stages, because it increases the time consumed to setup the simulation, and the difficulties associated with the thermal performance assessment of different design alternatives.

Therefore, an extensive investigation with series of simulation tests is performed to define a modeling approach that better fits to the purpose of this research.

Two sets of simulations are run and their results are compared to verify if, keeping the same U-value and heat capacity (HC), EnergyPlus models with virtual constructions[3] may accurately represent some similar models with a detailed construction input.

To represent the roof system, a four virtual layer construction is proposed while walls are represented by a three virtual layer construction, as illustrated respectively by *Figure 20* “a” and “b”.

[3] The virtual construction input method correspond to the use of a modeled construction composed by a set of materials whose thermal properties does not represent the real constructive components. The use of these virtual materials allows the independent variation of the U-value and heat capacity for the wall and roof system constructions.

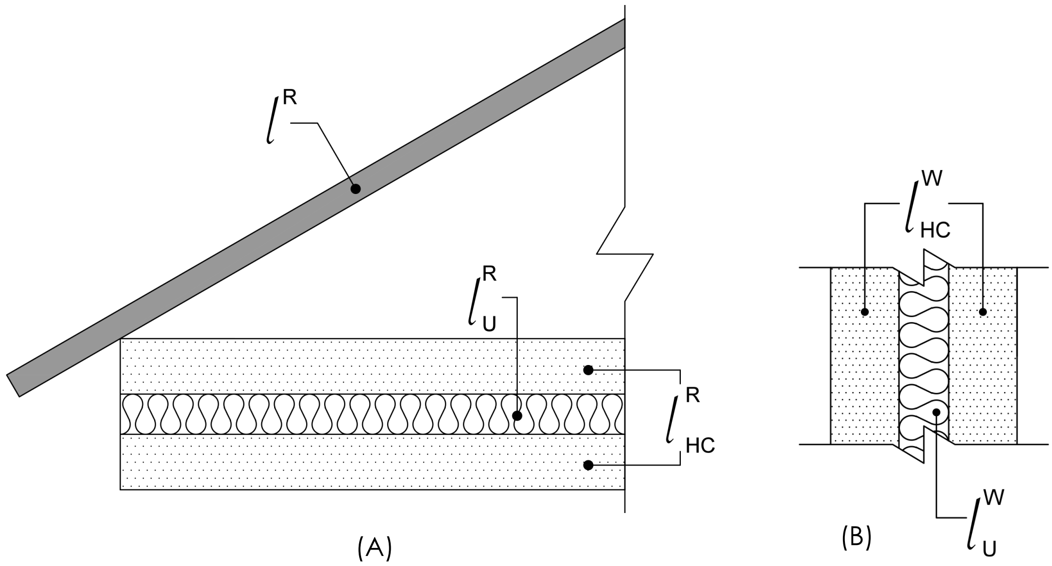


Figure 20: Roof (A) and wall (B) virtual construction scheme

Table 15 shows the wall and roof virtual layer properties; The variable field data considered in this benchmark test is indicated in bold. These material properties allow the independent variation of the Thermal Transmittance (U-Value) and Heat Capacity (HC) of the walls and roof system (roof and ceiling) by changing, respectively the fields: thermal resistance and material density.

Table 15: Roof and wall virtual material properties

LAYER	ENERGYPLUS INPUT GROUP	PROPERTIES			THERMAL RESISTANCE [m2.K/W]	HEAT CAPACITY [KJ/m2.K]
l^R	MATERIAL	ROUGHNESS	MEDIUM		0.01	14
		THICKNESS [m]	0.01			
		CONDUCTIVITY [W/(m2.K)]	1			
		DENSITY [Kg/m3]	1400			
		SPECIFIC HEAT [J/Kg.K]	1000			
		SOLAR ABSORPTANCE	0.7			
l^R_{HC}	MATERIAL	ROUGHNESS	MEDIUM		0.01	**VARIABLE**
		THICKNESS [m]	0.05			
		CONDUCTIVITY [W/(m2.K)]	5			
		DENSITY [Kg/m3]	**MIN**	**20**		
			MAX	**5560**		
		SPECIFIC HEAT [J/Kg.K]	1000			
l^R_U	MATERIAL: NO MASS	ROUGHNESS	MEDIUM		**VARIABLE**	-
		THERMAL RESISTANCE [m2.K/W]	**MAX**	**1.55**		
			MIN	**0.01**		
l^W_{HC}	MATERIAL	ROUGHNESS	MEDIUM		**0.01**	**VARIABLE**
		THICKNESS [m]	0.05			
		CONDUCTIVITY [W/(m^2.K)]	5			
		DENSITY [Kg/m^3]	**MIN**	**400**		
			MAX	**4450**		
		SPECIFIC HEAT [J/Kg.K]	1000			
		SOLAR ABSORPTANCE	0.7			
l^W_U	MATERIAL: NO MASS	ROUGHNESS	MEDIUM		**VARIABLE**	-
		THERMAL RESISTANCE [m^2.K/W]	**MAX**	**3.07**		
			MIN	**0.01**		

Four test series were used to analyze, individually and together, the thermal behavior of the wall and roof virtual construction (*Figure 21*). From test 01 to 03 the floor is considered adiabatic; in test 01 the roof is adiabatic and the heat transfer occurs just trough the walls; while test 02 presents the opposite scenario; In test 03 and 04 walls and roof are considered as heat exchanging surfaces, but with the difference that in the latter case the floor allows the heat transfer.

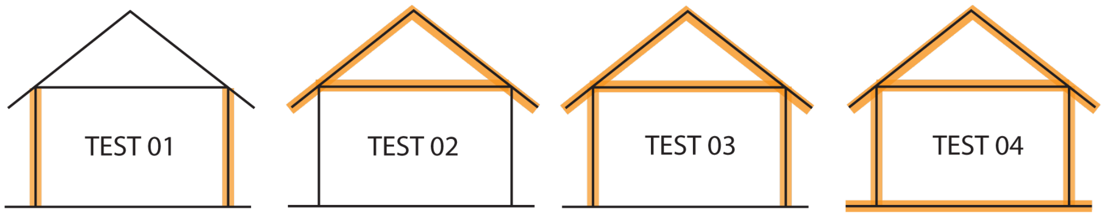


Figure 21: Virtual construction test series scheme

Table 16 shows and overview of the virtual construction cases analyzed. These tests are performed considering a specific Heat Capacity (HC) and Thermal Transmittance (U-value) value range that encompass the needs of this research. In test 01 to 03 the range extreme values are examined; for this purpose, a set of materials were combined creating some constructive systems that does not necessarily present actual building systems. In test 04 some Brazilian usual building systems were analyzed.

Table 16: Overview of the analyzed cases in the virtual construction test

CASE	TEST 01		TEST 02		TEST 03				TEST 04			
	Walls		Roof System		Walls		Roof System		Walls		Roof System	
	U *	HC **	U *	HC **	U *	HC **	U *	HC **	U *	HC **	U *	HC **
a	0.31	445	0.53	560	0.31	445	0.55	560	2.46	150	1.94	37
b	5.00	44	1.95	20	5.00	44	1.95	20	4.40	240	1.79	180
c	0.32	40	0.52	25	0.32	40	0.52	25	0.70	447	0.55	230
d	5.07	446	1.80	546	5.07	446	1.8	546	2.99	42	2.05	238

The geometry, the thermal properties of floor, doors, and glasses, the ventilation setup, the ground temperature, and the thermal zoning follow the definition showed on previous items; and no window shading devices were modeled.

The comparison between the operative temperatures predicted in EnergyPlus using different material input approaches is plotted in *Figure 22* to *Figure 24*. The vertical axis shows the real material detailed input model predictions, while the horizontal axis shows the virtual material input model prediction.

Considering wall and roof system Individually (test 01 and 02), it seems that the virtual wall construction present a better accuracy than the virtual roof construction; but the conjugated effect (test 03 and test 04) shows that the virtual modeling may represent the detailed modeling with good accuracy.

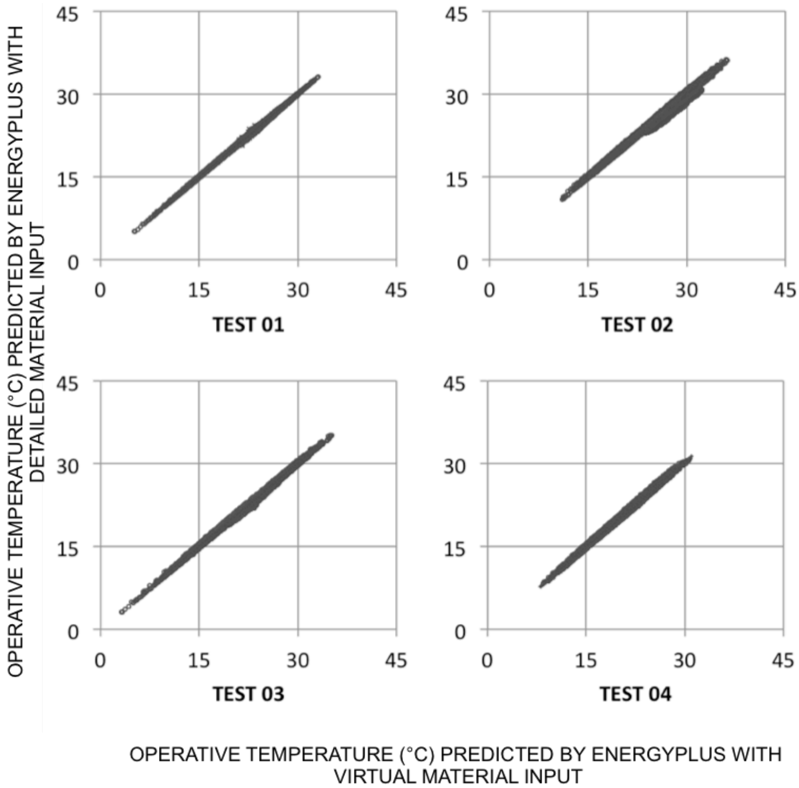


Figure 22: Operative temperature scatterplots of the real material detailed input model predictions against the virtual material input model predictions for Curitiba/PR.

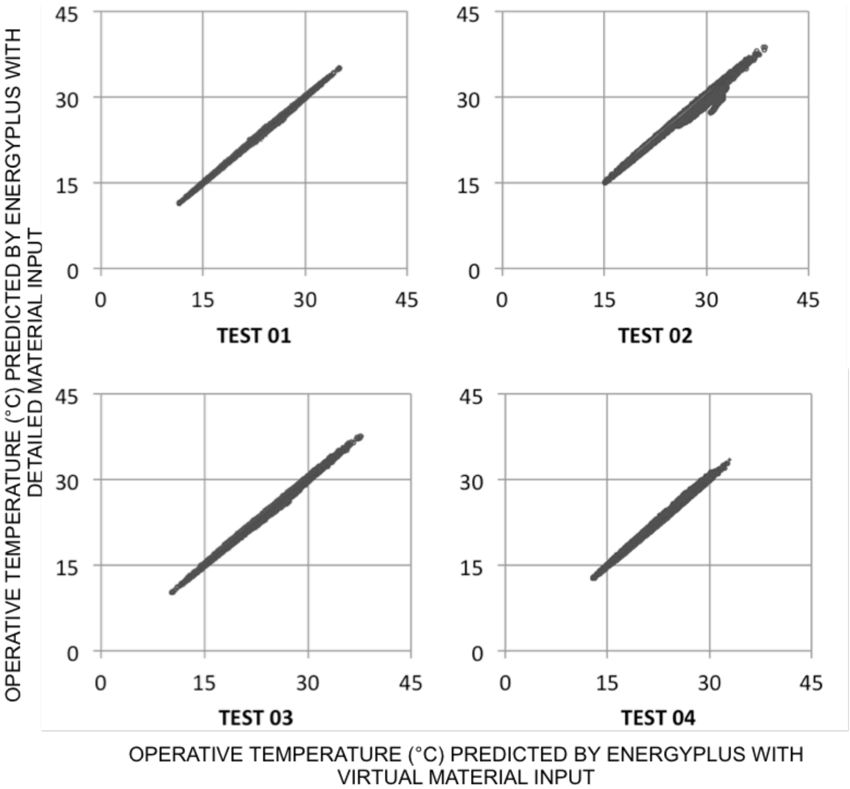


Figure 23: Operative temperature scatterplots of the real material detailed input model predictions against the virtual material input model predictions for São Paulo/SP.

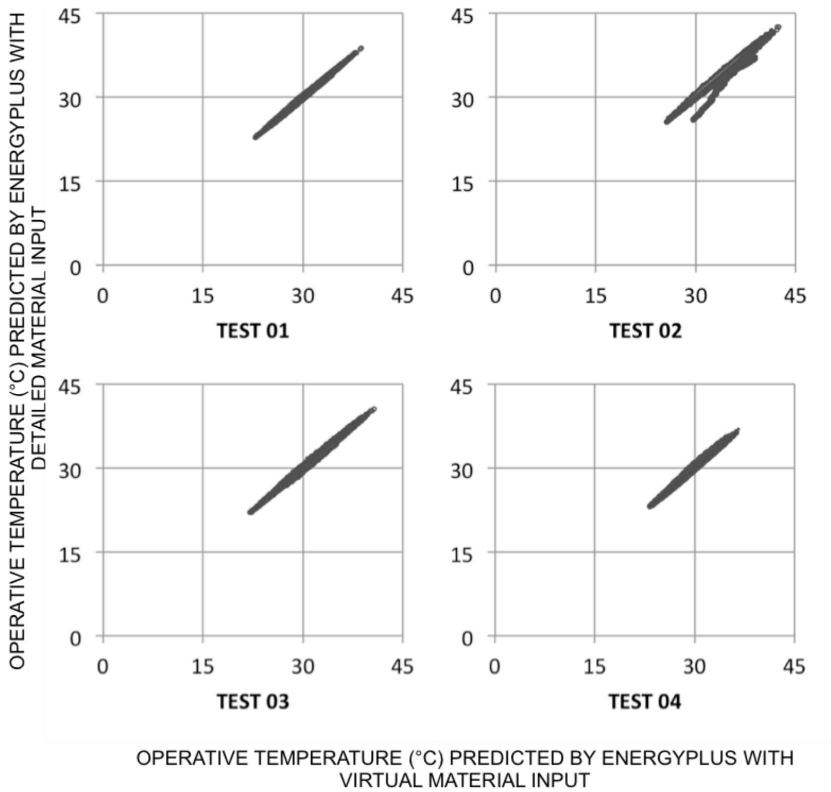


Figure 24: Operative temperature scatterplots of the real material detailed input model predictions against the virtual material input model predictions for Manaus/ AM.

The temperature variation during the winter and summer solstice days is also compared. *Figure 25* and *Figure 26* illustrate this comparison by showing the result of test 04 for the climate of São Paulo. Both modeling sets present similar behavior, and no time lag was found between the virtual and real material predictions. This comparative analysis was performed for all tests and climates, while not presented similar results were found.

This benchmark test result underlies the use of the virtual material construction input method in this research.

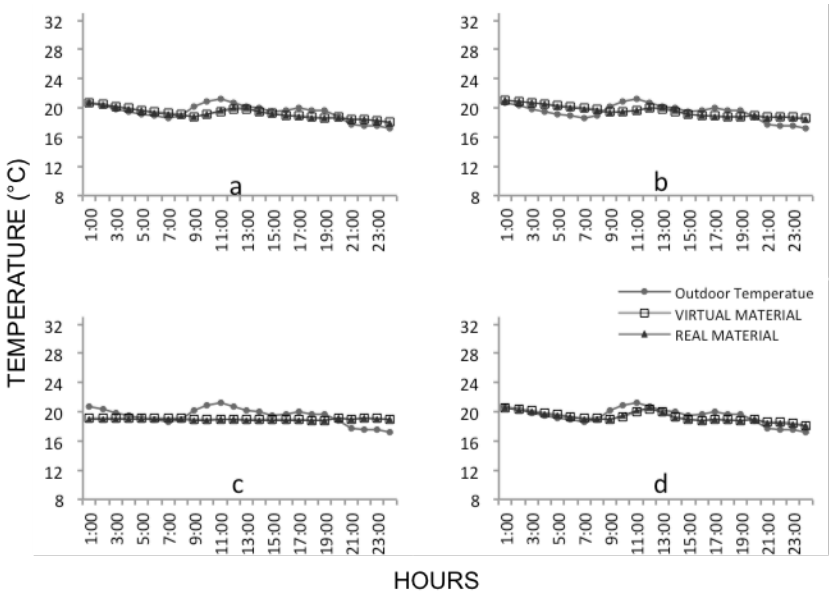


Figure 25: Comparison between the temperature variation during the winter solstice day for the virtual and detailed construction models

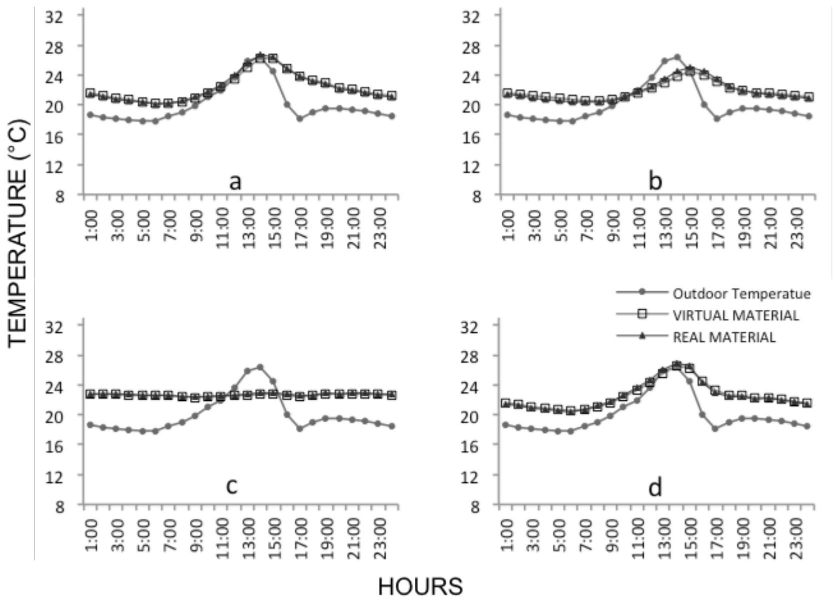


Figure 26: Comparison between the operative temperature variation during the summer solstice day for the virtual and detailed construction models

4.1.2. KEY DESIGN PARAMETER RANGES

The building design space to be explored in this research corresponds to the key parameter considered relevant to early design decisions and the value range associated to them. *Table 17* shows the parameter and their respective value range and *Figure 27* illustrate them.

Table 17: Key design parameters and their correspondent value range

	VARIABLE PARAMETERS	RANGE[4]	UNITS
01	Bedroom_1 Effective window ventilation area	50 to 100	%
02	Bedroom_2 Effective window ventilation area		
03	Living room Effective window ventilation area		
04	External Walls' Solar Absorptance	0.1 to 1.0	
05	Bedroom_1 Left Fin size	1 to 50	%
06	Bedroom_2 Left Fin size		
07	Living room Left Fin size		
08	Bedroom_1 Right Fin size		
09	Bedroom_2 Right Fin size		
10	Living room Right Fin size		
11	Bedroom_1 Overhang size	1 to 50	%
12	Bedroom_2 Overhang size		
13	Living room Overhang size		
14	Roof's Solar Absorptance	0.1 to 1.0	
15	North Axis/ Orientation in the terrain	0 to 359	Degrees
16	Bedroom_1 Window to Wall Ratio (WWR)	10 to 90	%
17	Bedroom_2 Window to Wall Ratio (WWR)		
18	Living room Window to Wall Ratio (WWR)		
19	External Walls' U-value	0.3 to 5.0	$W/(m^2. K)$
20	Internal Walls' U-value	0.3 to 5.0	$W/(m^2. K)$
21	Roof's U-Value	0.5 to 2.1	$W/(m^2. K)$
22	External Walls' Heat Capacity	40 to 455	$KJ/ (m^2. K)$
23	Internal Walls' Heat Capacity	40 to 455	$KJ/ (m^2. K)$
24	Roof's Heat Capacity	11 to 791	$KJ/ (m^2. K)$

[4] It spans a continuous range.

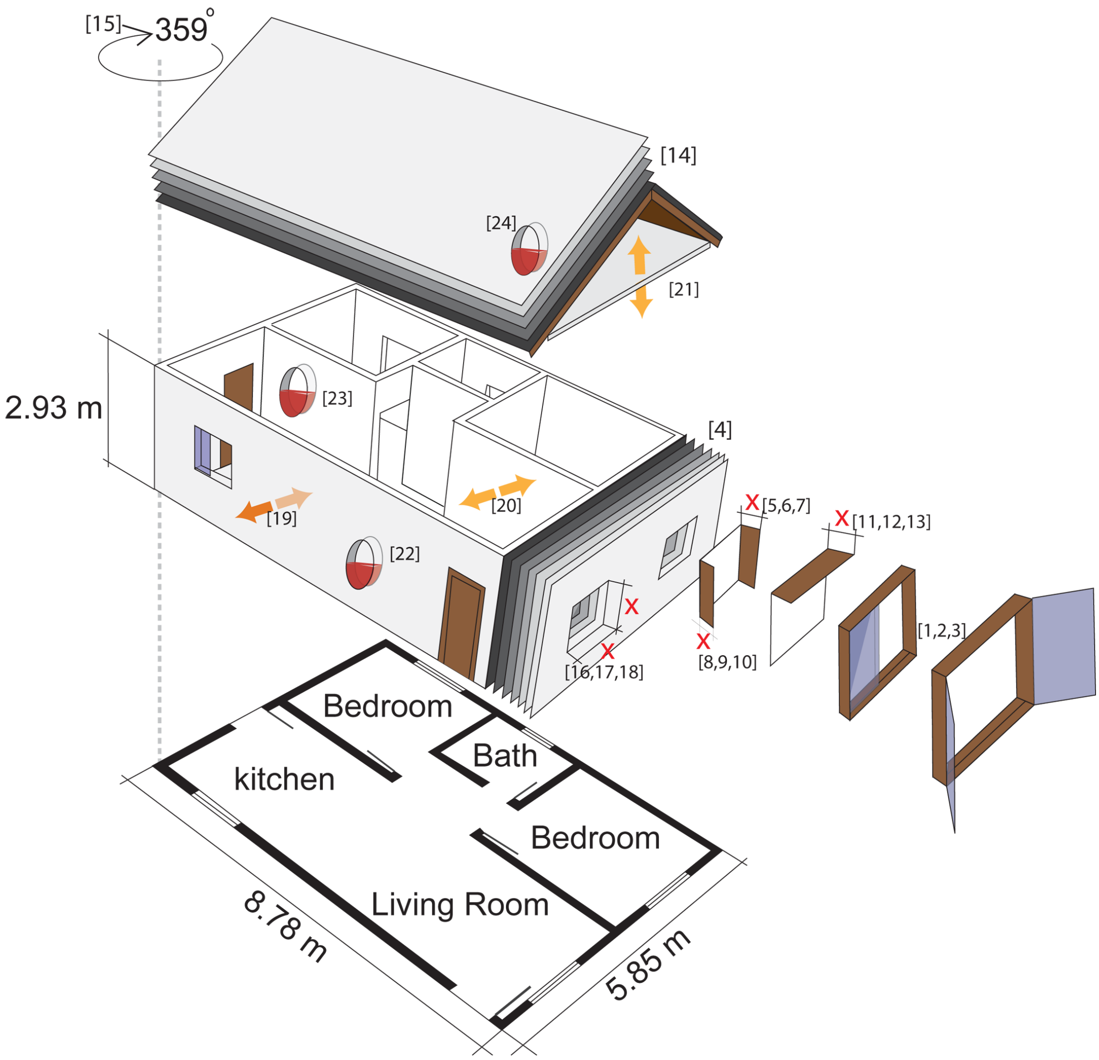


Figure 27: Overview of the variable parameters. Source: ROSSI et al., 2015.

4.1.3. BUILDING DESIGN SPACE OVERVIEW

Table 18 shows and overview of the building design space; it also references previous tables, figures, and items that describe in detail the considered parameters.

Table 18: Building design space overview

Location EnergyPlus weather file from Roriz (2012)	Curitiba/PR – bioclimatic zone 01 São Paulo/SP – bioclimatic zone 03 Manaus /AM – bioclimatic zone 08
Ground Temperature	Considered according to item 4.1.1.5.
Geometry	A detached low-cost house according to Figure 9
Window to Wall Ratio (WWR)	In long-stay rooms (bedrooms and living room): vary independently from 10% to 90% according to *Table 17*
eShading devices	The window fins and overhangs dimensions of long-stay rooms vary as a percentage of the window height The range is indicated in parameters 05 to 13 of *Table 17*. No shading devices are considered on the kitchen and bathroom windows. The base model also has 0.5m projecting eaves around all facades.
Window effective ventilation area	In long-stay rooms: vary independently from 50% to 100% of the window area (parameters 01 to 03 of *Table 17*). In kitchen: 50% of the window area In bathroom: 100% of the window area
Door type	Wood door – described in *Table 13*
Floor description	Crushed stone| Concrete| Plaster |Ceramic floor tile – Described in *Table 13*
External wall solar absorptance	0.1 to 1.0 - parameter 04 of *Table 17*
External wall heat capacity	0.1 to 1.0 - parameter 22 of *Table 17*
External wall U-Value	0.3 to 5.0 W/(m^2.K) – parameter 19 of *Table 17*
Internal wall heat capacity	40 t0 455 KJ/(m^2.K) – parameter 23 of *Table 17*
Internal wall U-value	40 t0 455 W/(m^2.K) – parameter 20 of *Table 17*
Roof solar absorptance	0.1 to 1.0 - parameter 14 of *Table 17*
Roof system heat capacity	11 to 791 KJ/(m^2.K) – parameter 24 of *Table 17*
Roof system U-value	0.5 to 2.1 W/(m^2.K) – parameter 21 of *Table 17*
Internal gains	Based on the Brazilian Energy Efficiency Technical Requirements for Residential Building Performance (INMETRO, 2012). Described in item 4.1.1.3.
Ventilation setup	The natural ventilation is allowed from 7:00 am to 10:00 pm. The item 4.1.1.4. describes the restrictions that define whether or not the ventilation actually occurs.

4.2. MONTE CARLO SIMULATION

The Monte Carlo simulation was used to explore the building design space and provide the thermal comfort associated with each building instance. This task deals with three steps: (1) Sampling/ Substitution Routine; (2) EnergyPlus simulation; and (3) Post-processing data.

4.2.1. SAMPLING/SUBSTITUTION ROUTINES

To sample the design space, the Monte Carlo method was used to create a combination of values between the key parameter ranges considered. A Python script (YANG et al., 2015a) was used to automatically substitute, in the base model, the combination of values sampled by Monte Carlo. The script incorporates regular expressions to locate EnergyPlus objects by name and type to update de input data file. To obtain an exhaustive coverage of the design space, the Monte Carlo simulation included 10,000 iterations for each meta model set of the three analyzed climates.

Pearl Scripts developed by Hygh (2012) was translated and adapted to encompass the needs of this research, so they underlie the Python from Yang et al., (2015a). During the development of this code, the master student was in charge of reviewing the generated IDFs and to report the existence of errors and bugs.

Using a diff tool about 200 generated IDFs were compared to the base model to test if: (a) the changes were occurring only in the lines that were supposed to, and (b) the variable parameters value complies with the defined range. In addition, a couple of simulations were run to verify if an IDF generated by the code shows the same result as a manually generated IDF with the same values. When all these quiestions were affirmatively answered, than the code writing was finalized and the Sampling/ Substitution Routine task could be completed.

4.2.2. ENERGYPLUS SIMULATION

The software EnergyPlus 8.1 was utilized to run 10,000 simulations for each meta-model set of the three analyzed climates. The simulations were performed in a 21-nodes, 656 cores Linux cluster at the Department of Civil Construction, and Environmental Engineering of the North Carolina State University. These simulations cases are used to generate and test the accuracy of the regression models.

4.2.2.1. POST-PROCESSING DATA: PARAMETER DOMAINS AND PERFORMANCE METRICS

A Python script (YANG el al., 2015b) was developed to post-process the EnergyPlus output data and prepare the data for the regression analysis.

Two different tasks must be performed: (a) to extract the combination of the key parameter values from the EnergyPlus IDFs, and (b) to calculate the desired performance metric by extracting the EnergyPlus Output from CSV. Then, two new CSV files were created for each of the three locations. One of the CSVs will contain a list of the 10,000 key parameter value combinations, while the other will contain the performance metric calculated for the same 10,000 cases.

This group of CSVs pairs, generated from the post-processing data script, are used as the input for the multivariate regression analysis.

4.3. MULTIVARIATE REGRESSION

Multivariate regressions are performed on results for degree-hours of heat and cold discomfort on the 24 independent parameters (*Table 17*). Of the 10.000 simulation discomfort results, sixty percent are used to estimate the regression equation and the remaining forty percent are used to test its accuracy to predict actual simulation results.

The institutional version of Matlab R2013a (MATHWORKS INC., 2013) is used to perform the regression models according to the following characteristics:

- The use of a p-enter of 0.05 and a p-remove value of 0.1
- The key design parameters are used to compose the predictor variable “X”
- The annual degree hour of discomfort by heat and by cold compose the response variable “y

Linear regression coefficients are generated, and the form of the regression equation to predict heat and cold discomfort is:

$$y(x_1, x_2, x_3, \dots, x_n) = \beta_0 + \sum_{j=1}^{n} \beta_j x_j \qquad \text{(Equation 09)}$$

where: y is the predicted degree-hour of heat and cold discomfort, x are the parameter values, β_0 is the independent variable (or interceptor), and β_j are the correspondent coefficients.

The regression model performed for the degree-hour of heat and cold discomfort on the 24 key design parameters may present some unexplained variances, limiting the certainty of the generated predictions. In these cases the accuracy may be improved by adding additional terms to the model; these supplementary terms are each a function of one or more of the 24 parameters originally included in the regression analysis.

According to each regression peculiarities some of the following procedure steps are applied:

StepWiseFit (SWF)

Regression analysis that uses stepwisefit in MATLAB for the degree-hour of heat and cold discomfort with respect to the 24 pure terms – the considered key design parameters. This regression technique tests the influence of each predictor variable “x” in the response variable “y” according to the specified limits (in this case: p-enter = 0.05 and p-remove = 0.1); the terms with p-value lower than 0.05 are included in the regression, while grater p-values cause the exclusion of the term.

StepwiseLM (LM)

Regression analysis that uses stepwiselm in MATLAB for the degree-hour of heat and cold discomfort with respect to the 24 ‘pure’ terms. This regression technique allows for more flexibility in the modeling and also uses forward and backward stepwise regression to automatically check for cross terms and adds them to the regression equation. The same p-enter and p-remove of SWF is considered.

StepwiseLM with INverse terms (LMwIN)

Regression analysis that uses stepwiselm in MATLAB for the degree-hour of heat and cold discomfort with respect to an expanded set of terms in the predictor variable “x” for the regression. Twenty-four additional data points, which corresponds to the inverse of each one of the 24 'pure' terms were included in the former "x" variable set (e.g., term 25 is the inverse of the term 01, term 48 is the inverse of term 24, etc.). The resultant models consist of 'pure' terms, cross terms and inverse terms.

No Zero plots (NZ)

If a great number of zero values for degree hours of discomfort are found as a response for different key design parameters combinations, difficulties on the fitting of the regression model to the data may occur because of the large amount of unique input data sets that yield a singular output – zero. Therefore, the runs that yielded degree hours of discomfort = 0 are removed from the original data sets of 6000 points, and the remaining simulation results are used to perform the regressions and to validate the generated models.

Regression floor (floor)

The degree-hour of discomfort obtained by EnergyPlus simulation runs cannot give negative values; thus, the regression model is disallowed to give negative values by the following statement: if regression value < 0, result = 0, else result = regression value.

Quadratic regression (Q)

Allows the inclusion of quadratic or polynomial terms to the predictor variable "X".

5. RESULTS AND ANALYSIS

5.1. GENERAL TECHNIQUE

Monte Carlo simulations are performed to explore the building design space; for each climate 10.000 combinations of the variable design parameters are compiled into sets of Energy Plus inputs. The simulation outputs are the annual degree-hours of discomfort by heat and by cold. From this dataset 60% are used to build a multivariate regression model with the goal of accurately predicting Energy Plus outputs, while the remaining 40% are used to validate the model.

During the regression modeling, several steps are performed to increase the model accuracy: **(a)** the first step looked for individual effects of the 24 key design parameters (*Table 17*) on the regression. Then **(b)** cross terms, such as "external wall solar absorptance" multiplied by "external wall U-value, were added to recognize meaningful combinations of design parameters and their effect on passive heating and cooling. **(c)** Also, some design parameters have an influence with others as an inverse, then the initial key design parameters were expanded to include the inverse of each value; the model accuracy was improved and its complexity was increased. Finally, **(d)** the upper bounds of the model were expanded from "interactions" to "quadratic", allowing squared terms in each model.

5.2. CHALLENGES AND SOLUTIONS

Because the considered metric is the degree-hours of discomfort, just positive numbers are allowed; the lack of discomfort always output as zero. Therefore, if no discomfort is computed, different combinations of input variables may result in the same output value: zero. Similar researches (AL GHARABLY; DECAROLIS; RANJITHAN, 2015; HYGH et al., 2012)focused on regression models to assess energy consumption, were able to quantify negative heating and cooling loads, linking each input set to a unique output value. From these, two observation may be highlighted: (1) any negative value predicted by the regression model should be interpreted as zero, and (2) the regression model, in trying to fit numerous data sets to the same output value, may not generate an accurate fit.

To address the first observation, a post-processing step was added, setting any negative values predicted by the regression model to zero defining a “floor” on the regression values, increasing the accuracy of each model as measured by R^2 values. The second issue is the preponderance of EnergyPlus zero values for heat discomfort in the climates of Curitiba/PR (81% of the total data points generated in EnergyPlus were zero values) and São Paulo/SP (60% of zero values). For these cases the use of the standard regression methods on this large amount of zero values linked to different combinations of parameters input, generating less accurate models. Therefore, an alternative solution was pursued.

The method employed was to train the model using only the non-zero (NZ) values of the output. By first eliminating all data sets that had a zero derived from the EnergyPlus output. Next, 75% of the NZ data set was randomly chosen and used to build the regression model, saving the remaining 25% for validation. The resultant model had a much better degree of accuracy in predicting the NZ values. However, the primary drawback of this approach is that the “NZ” models could not accurately predict low or zero values for the entire dataset.

5.3. REGRESSION RESULTS AND VALIDATION

The regression analyses resulted in seven meta-models:

- 03 for Curitiba/PR:
  - Discomfort by cold
  - Discomfort by heat (standard approach)
  - Discomfort by heat (NZ approach)
- 03 for São Paulo/SP:
  - Discomfort by cold
  - Discomfort by heat (standard approach)
  - Discomfort by heat (NZ approach)
- 01 for Manaus
  - Discomfort by heat (standard approach)

The cities of Curitiba and São Paulo show a predominance of discomfort by cold and count with low degree-hours of discomfort by heat. So concerning the discomfort by heat many combinations of parameters input report to the same output: zero, leading to less accurate models. Therefore, two regression alternatives were tested, resulting in 02 different meta-models to predict the discomfort by heat in each of these cities. The city of Manaus counts only with one meta-model to predict the discomfort by heat; No discomfort by cold was found in the EnergyPlus simulation, so there was no data available to perform the regressions.

The coefficients of each meta-model are shown in the appendices and a brief description of the equation terms and their relation to the building OE parameters are indicated in the following tables.

Table 19 shows a summary of the Curitiba meta-models regression terms and Table 20 indicates the number of terms that are related to each OE parameter. From the total of terms in the 'discomfort by cold' model 69% are related to the OE parameters. In the 'discomfort by heat' models, created with the standard and NZ approaches, the OE parameters are present in 95% and 86%, respectively.

Table 19: Number of terms of the regressions for Curitiba – PR.

	Pure	Inverse	Quadratic	Cross	TOTAL
DISCOMFORT BY COLD	20	4	10	117	**151**
DISCOMFORT BY HEAT	8	4	5	47	**64**
DISCOMFORT BY HEAT (NZ)	13	5	6	46	**70**

Table 20: Number of terms related to opaque envelope parameters in the regressions for Curitiba – PR.

	OPAQUE ENVELOPE (OE) PARAMETERS	**TERMS**				
		Pure	Inverse	Quadratic	Cross	
					Only OE	Others
CURITIBA/PR: REGRESSION MODELS TO PREDICTTHE ANNUAL DISCOMFORT: BY COLD	External Walls' Solar Absorptance	1	0	1	3	3
	Roof's Solar Absorptance	1	0	1	6	6
	External Walls' U-value	1	0	1	7	6
	Internal Walls' U-value	0	0	0	0	0
	Roof's U-Value Terms	1	0	0	6	6
	External Walls' Heat Capacity	1	0	1	5	4
	Internal Walls' Heat Capacity	1	1	1	11	19
	Roof's Heat Capacity	1	1	2	10	20
	TOTAL OF TERMS	**7**	**2**	**7**	**24**	**64**
BY HEAT	External Walls' Solar Absorptance	1	0	1	7	0
	Roof's Solar Absorptance	1	0	1	8	1
	External Walls' U-value	1	0	1	7	1
	Internal Walls' U-value	0	0	0	0	0
	Roof's U-Value Terms	1	1	1	13	5
	External Walls' Heat Capacity	0	1	0	8	3
	Internal Walls' Heat Capacity	0	1	0	8	3
	Roof's Heat Capacity	1	1	1	13	2
	TOTAL OF TERMS	**5**	**4**	**5**	**32**	**15**
BY HEAT (NZ)	External Walls' Solar Absorptance	1	0	0	6	2
	Roof's Solar Absorptance	1	0	1	8	2
	External Walls' U-value	1	1	1	8	2
	Internal Walls' U-value	0	0	0	0	0
	Roof's U-Value Terms	1	1	1	11	2
	External Walls' Heat Capacity	1	1	1	11	2
	Internal Walls' Heat Capacity	0	1	0	6	3
	Roof's Heat Capacity	1	0	1	8	3
	TOTAL OF TERMS	**6**	**4**	**5**	**29**	**16**

Table 21 shows a summary of the São Paulo meta-models regression terms, and *Table 22* indicates the number of terms that are related to each OE parameter. In the model that predicts the discomfort by cold 65% of the terms are related to the OE parameters, and for the heat discomfort models the OE parameters are present in 84% and 90% of the terms from the meta-models developed with the standard and NZ approaches, respectively.

Table 21: Number of terms and R^2 of the regressions for São Paulo - SP.

	Pure	Inverse	Quadratic	Cross	TOTAL
DISCOMFORT BY COLD	19	5	11	92	**127**
DISCOMFORT BY HEAT	10	2	9	53	**76**
DISCOMFORT BY HEAT (NZ)	14	5	8	70	**97**

Table 22: Number of terms related to opaque envelope parameters in the regressions for São Paulo - SP.

		OPAQUE ENVELOPE (OE) PARAMETERS	**TERMS**				
			Pure	Inverse	Quadratic	Cross	
						Only OE	Others
SÃO PAULO/SP: REGRESSION MODELS TO PREDICT THE ANNUAL DISCOMFORT:	**BY COLD**	External Walls' Solar Absorptance	1	0	1	5	5
		Roof's Solar Absorptance	1	0	1	5	11
		External Walls' U-value	1	0	1	8	7
		Internal Walls' U-value	0	0	0	0	0
		Roof's U-Value Terms	1	0	0	7	3
		External Walls' Heat Capacity	1	1	1	9	6
		Internal Walls' Heat Capacity	1	0	1	5	4
		Roof's Heat Capacity	1	1	2	11	6
		TOTAL OF TERMS	**7**	**2**	**7**	**25**	**42**
	BY HEAT	External Walls' Solar Absorptance	1	0	1	6	2
		Roof's Solar Absorptance	1	0	1	6	5
		External Walls' U-value	1	0	1	6	4
		Internal Walls' U-value	0	0	0	0	0
		Roof's U-Value Terms	1	0	1	6	5
		External Walls' Heat Capacity	0	1	1	6	3
		Internal Walls' Heat Capacity	1	0	1	6	4
		Roof's Heat Capacity	0	1	1	6	6
		TOTAL OF TERMS	**5**	**2**	**7**	**21**	**29**
	BY HEAT (NZ)	External Walls' Solar Absorptance	1	0	1	8	3
		Roof's Solar Absorptance	1	0	1	9	4
		External Walls' U-value	1	0	1	8	3
		Internal Walls' U-value	0	0	0	0	0
		Roof's U-Value Terms	1	1	1	10	3
		External Walls' Heat Capacity	1	1	1	14	7
		Internal Walls' Heat Capacity	1	0	1	8	4
		Roof's Heat Capacity	1	1	2	15	9
		TOTAL OF TERMS	**7**	**3**	**8**	**36**	**33**

Table 23 shows a summary of the Manaus meta-model regression terms, and *Table 24* indicates the number of terms that are related to each OE parameter. From the total of terms 73% are related to the OE parameters.

***Table 23: Number of terms and R^2 of the regressions for Manaus - AM*.**

	Pure	Inverse	Quadratic	Cross	TOTAL
DISCOMFORT BY HEAT	16	8	13	105	**142**

Table 24: Number of terms related to opaque envelope parameters in the regressions for Manaus – AM.

	OPAQUE ENVELOPE (OE) PARAMETERS	**TERMS**				
		Pure	Inverse	Quadratic	Cross	
					Only OE	Others
MANAUS/AM: REGRESSION MODEL TO PREDICT ANNUAL DISCOMFORT BY HEAT	External Walls' Solar Absorptance	1	0	1	8	8
	Roof's Solar Absorptance	1	0	1	8	9
	External Walls' U-value	1	1	1	9	6
	Internal Walls' U-value	0	0	0	0	0
	Roof's U-Value Terms	1	0	1	6	7
	External Walls' Heat Capacity	1	0	1	8	8
	Internal Walls' Heat Capacity	0	1	1	7	6
	Roof's Heat Capacity	1	1	1	12	15
	TOTAL OF TERMS	**6**	**3**	**7**	**29**	**59**

Tables 20, 22, and 24 highlight the importance of considering the OE parameters in the assessment of building thermal discomfort.

The results of the linear regression models are summarized in *Table 25*, which demonstrates that while some values have good fit in terms of R^2 values, there is still significant average % error, indicating a positive or negative bias. There are two models for CTB and SP Heat, which demonstrate two different approaches discussed above. The coefficient of variation of the root mean square error (CV(RMSE)) has been calculated along with the RMSE.

Table 25: Result error analysis

		Curitiba/ PR	São Paulo/ SP	Manaus/AM
Discomfort by cold	RMSE	569.37	149.48	
	CV(RMSE)	0.0651	0.0436	
	NMBE	1.3103E-05	4.2195E-04	
	Avr % Error	0.11%	0.11%	
	R^2	**0.9515**	**0.982**	
Discomfort by heat	RMSE	13.46	30.12	167.09
	CV(RMSE)	4.2409	1.7853	0.4098
	NMBE	-0.700	-0.363	-0.080
	Avr % Error	804.14%	2162.68%	5517.61%
	R^2	**0.6107**	**0.7464**	**0.9505**
Discomfort by heat (NZ)	RMSE	58.26	67.56	
	CV(RMSE)	18.3563	4.0049	
	NMBE	-9.537	-1.815	
	Avr % Error	1592.74%	1112.14%	
	R^2 (NZ/ all)	**.8323 / .0529**	**.9078 / 0.3749**	

Where:

$$RMSE = \sqrt{\frac{sum\ of\ squared\ residuals}{(n-p-1)}}$$

$$CV(RMSE) = \frac{1}{\bar{y}}\sqrt{\frac{sum\ of\ squared\ residuals}{(n-p-1)}} = \frac{RMSE}{\bar{y}}$$

$$\%\ Error = \frac{y_{model} - y_{EnergyPlus}}{y_{EnergyPlus}}$$

$$Average\ \%\ Error = \frac{\sum_{i=1}^{n}\frac{y_{model_i} - y_{EnergyPlus_i}}{y_{EnergyPlus_i}}}{n}$$

Figure 28 plots the degree-hours of discomfort predicted by the regression models (horizontal axis) against the discomfort calculated based on the EnergyPlus outputs (vertical axis) for each climate. The lines (x=y) represent a perfect agreement between the EnergyPlus and the meta-model result. As previously mentioned, the heat model for Curitiba and São Paulo did not achieve the same level of accuracy as the other models, and an alternative regression method with a NZ approach was tested. *Figure 29* shows the validation of the Curitiba and São Paulo Heat – NZ models. Each model was tested with two validation data sets: (a) NZ VALUES ONLY, which exclude all simulated cases that resulted in 0 °Ch of discomfort by heat; and (b) ALL VALUES, which consider the zero values.

The NZ models show a good fit concerning the first validation set, with R^2=0.83 for Curitiba and R^2=0.91 for São Paulo, but a poor fit concerning the second data set, with R^2=0.06 for Curitiba and 0.37 for São Paulo, indicating that the NZ models are unable to give accurate prediction when the degree-hours of discomfort are low or nonexistent.

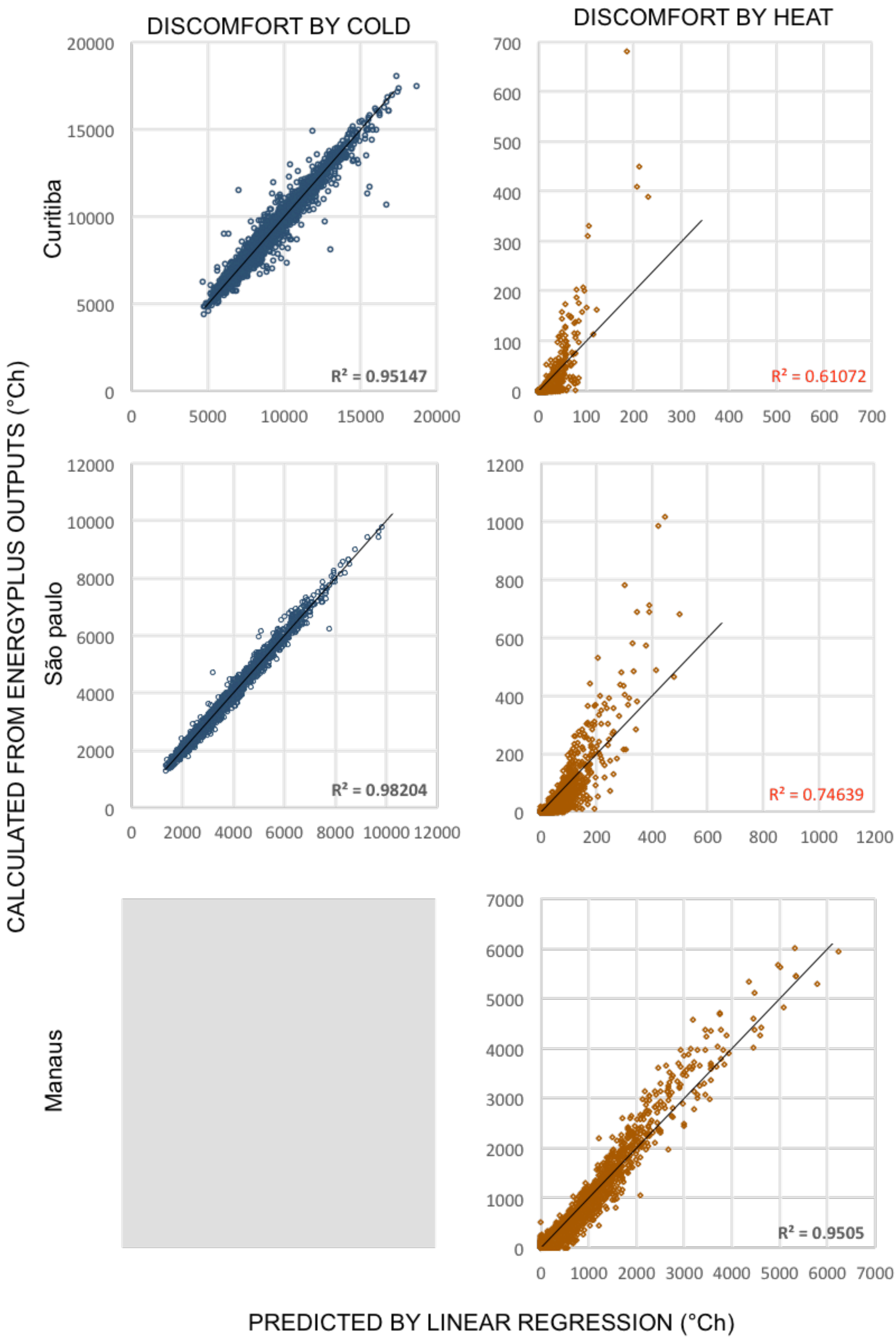


Figure 28: Validation of the discomfort by cold and by heat regression models. Lines represent perfect agreement between the result from EnergyPlus (vertical axis) and prediction by regression models (horizontal axis)

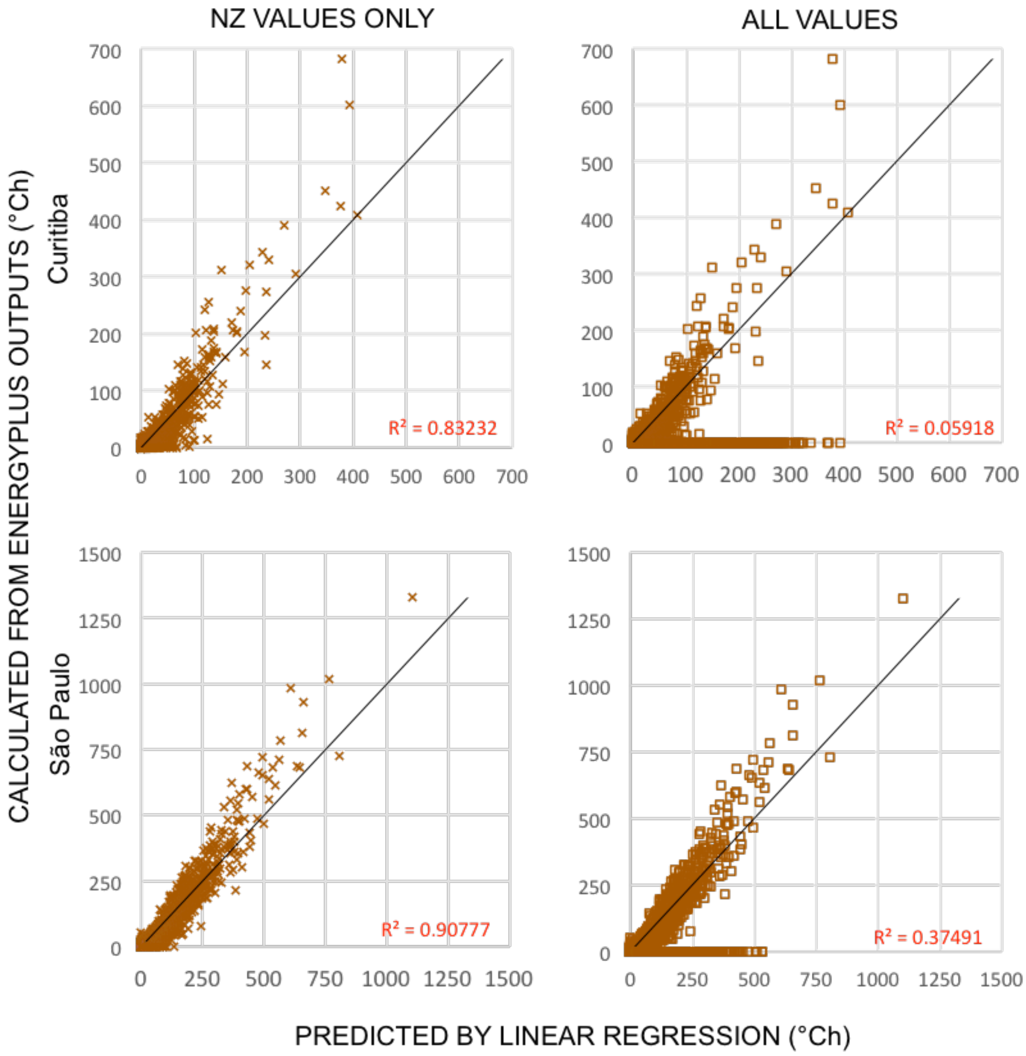


Figure 29: Validation of the discomfort by heat regression models with two data sets: NZ VALUES ONLY excluding the 0 values from the validation set, and ALL VALUES that include the 0 values. Lines represent perfect agreement between the result from EnergyPlus (vertical axis) and prediction by regression models (horizontal axis)

5.4. META-MODEL APPLICATION TEST

An application test is performed to verify the meta-models' potentiality to assess LCH thermal performance and to guide the decisions concerning the building opaque envelope during the early design stages.

Table 26 shows and overview of the meta-model application test setup; the fixed values are indicated and the variable parameters (External wall and roof solar absorptance, external wall and roof U-value, external wall and roof heat capacity) are highlighted.

Table 26: Overview of the meta-model application test

	META-MODEL INPUT PARAMETERS	VALUES
01	Bedroom_1 Effective window ventilation area	50%
02	Bedroom_2 Effective window ventilation area	
03	Living room Effective window ventilation area	
04	**External Walls' Solar Absorptance**	**Varies according to table 27**
05	Bedroom_1 Left Fin size	1%
06	Bedroom_2 Left Fin size	
07	Living room Left Fin size	
08	Bedroom_1 Right Fin size	
09	Bedroom_2 Right Fin size	
10	Living room Right Fin size	
11	Bedroom_1 Overhang size	1%
12	Bedroom_2 Overhang size	
13	Living room Overhang size	
14	**Roof's Solar Absorptance**	**Varies according to table 27**
15	North Axis/ Orientation in the terrain	270
16	Bedroom_1 Window to Wall Ratio (WWR)	14
17	Bedroom_2 Window to Wall Ratio (WWR)	
18	Living room Window to Wall Ratio (WWR)	
19	**External Walls' U-value**	**Varies according to table 27**
20	Internal Walls' U-value	2,78 W/(m². K)
21	**Roof's U-Value**	**Varies according to table 27**
22	**External Walls' Heat Capacity**	
23	Internal Walls' Heat Capacity	209 KJ/ (m². K)
24	**Roof's Heat Capacity**	**Varies according to table 27**

Table 27 shows the variable parameters values for the 72 cases used to test each of the seven meta-models developed. From case 1 to 12 external wall properties are kept constant while four roof systems (roof + attic + ceiling) U-value and HC combinations are varied within three roof solar absorptance values. In cases 13 to 24 roof system properties remain constant and four wall U-value and HC combinations are tested within the same three solar absorptance values. Intermediate wall and roof systems HC values are considered in these cases; in the following cases the same wall and roof U-value and solar absorptance variations are repeated considering low and high HC values for the roof system (cases 25 to 36 and cases 37 to 48, respectively) and for the external walls (cases 49 to 60 and 61 to 72). The analyzed cases represent usual Brazilian low-cost house OE properties (MARQUES, 2013) and

their U-value, HC and absorptance are varied according to the ranges defined by national standards and regulation

Table 27: Variable parameters for the meta-model input

CASE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
External Walls' Solar Absorptance	0.6											
Roof's Solar Absorptance	0.9				0.6				0.3			
Wall U-value (W/m². K)	2.11											
Roof U-Value (W/m². K)	0.55	1.8	2.57	3.79	0.55	1.8	2.57	3.79	0.55	1.8	2.57	3.79
Wall HC (KJ/m². K)	156											
Roof HC (KJ/m². K)	168	181	176	189	168	181	176	189	168	181	176	189
CASE	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
External Walls' Solar Absorptance	0.9				0.6				0.3			
Roof's Solar Absorptance	0.6											
Wall U-value (W/m². K)	1	2.11	3.05	4.39	1	2.11	3.05	4.39	1	2.11	3.05	4.39
Roof U-Value (W/m². K)	1.8											
Wall HC (KJ/m². K)	161	156	156	161	161	156	156	161	161	156	156	161
Roof HC (KJ/m². K)	181											
CASE	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
External Walls' Solar Absorptance	0.6											
Roof's Solar Absorptance	0.9				0.6				0.3			
Wall U-value (W/m². K)	2.11											
Roof U-Value (W/m². K)	0.55	1.8	2.57	3.79	0.55	1.8	2.57	3.79	0.55	1.8	2.57	3.79
Wall HC (KJ/m². K)	156											
Roof HC (KJ/m². K)	20											
CASE	**37**	**38**	**39**	**40**	**41**	**42**	**43**	**44**	**45**	**46**	**47**	**48**
External Walls' Solar Absorptance	0.6											
Roof's Solar Absorptance	0.9				0.6				0.3			
Wall U-value (W/m². K)	2.11											
Roof U-Value (W/m². K)	0.55	1.8	2.57	3.79	0.55	1.8	2.57	3.79	0.55	1.8	2.57	3.79
Wall HC (KJ/m². K)	156											
Roof HC (KJ/m². K)	700											
CASE	**49**	**50**	**51**	**52**	**53**	**54**	**55**	**56**	**57**	**58**	**59**	**60**
External Walls' Solar Absorptance	0.9				0.6				0.3			
Roof's Solar Absorptance	0.6											
Wall U-value (W/m². K)	1	2.11	3.05	4.39	1	2.11	3.05	4.39	1	2.11	3.05	4.39
Roof U-Value (W/m². K)	1.8											
Wall HC (KJ/m². K)	40											
Roof HC (KJ/m². K)	181											
CASE	**61**	**62**	**63**	**64**	**65**	**66**	**67**	**68**	**69**	**70**	**71**	**72**
External Walls' Solar Absorptance	0,9				0,6				0,3			
Roof's Solar Absorptance	0,6											
Wall U-value (W/m². K)	1	2,1	3,05	4,39	1	2,1	3,05	4,39	1	2,1	3,05	4,39
Roof U-Value (W/m². K)	1,8											
Wall HC (KJ/m². K)	400											
Roof HC (KJ/m². K)	181											

The following figures show representative results of the meta-models application test. While not presented, the remaining cases show similar behavior. Each point of *Figure 30* shows the discomfort by cold for São Paulo and Curitiba, and the discomfort by heat for Manaus; charts "a" to "c" plot the cases 1 – 12 of *Table 27*, and charts "c" to "d" plot the cases 13 – 24 of the same table. *Figure 31* shows the discomfort by heat for São Paulo and Curitiba predicted by the standard and the NZ models for each location. The charts for São Paulo plot the result of the cases 1 to 12, and the charts for Curitiba plot cases 13 to 24; charts "a" and "b" show the prediction of the models developed with the standard approach, while "c" and "d" concerns the NZ approach models.

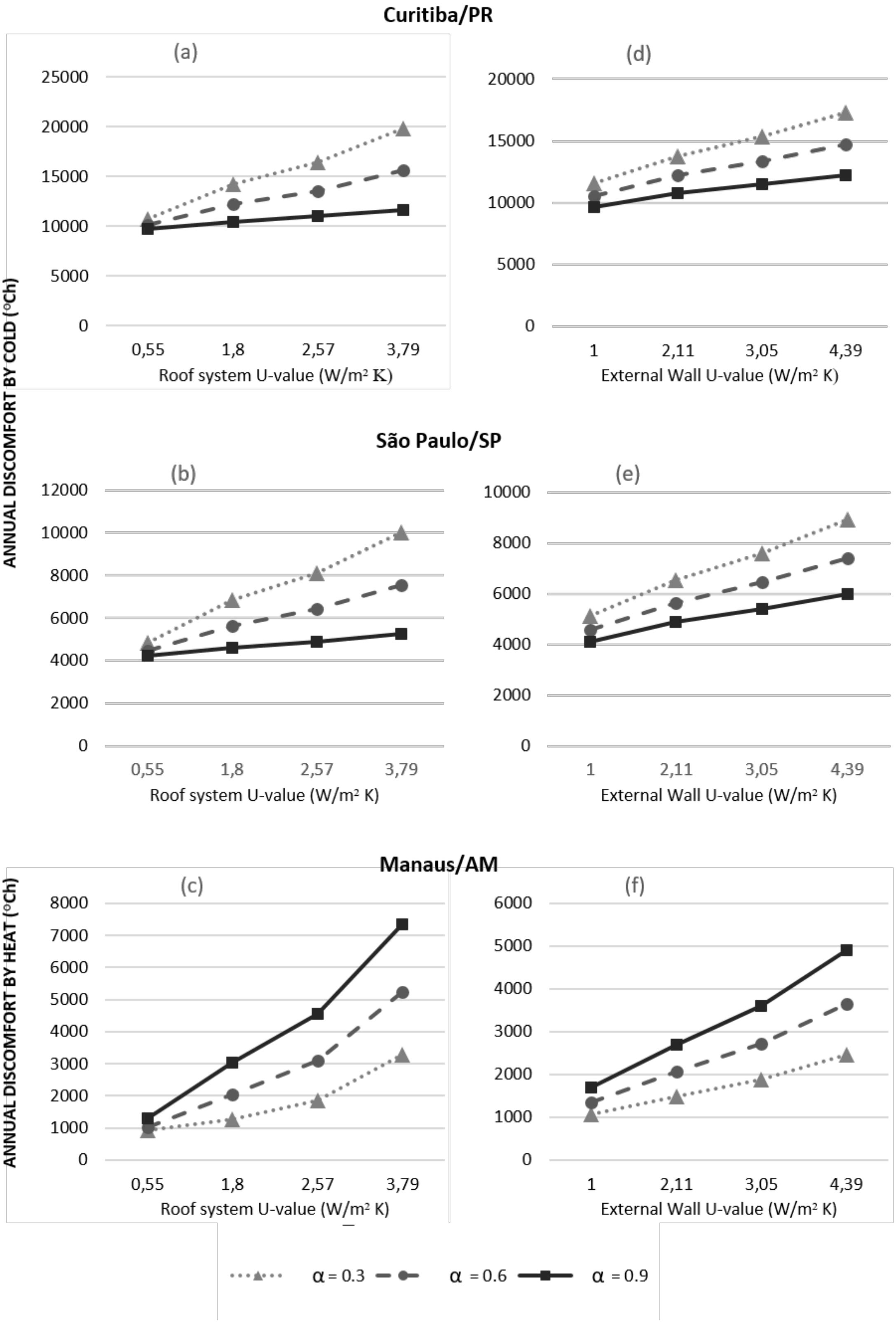


Figure 30: Meta-model application test results of cases 1 to 24 for São Paulo and Curitiba – discomfort by cold – and for Manaus – discomfort by heat.

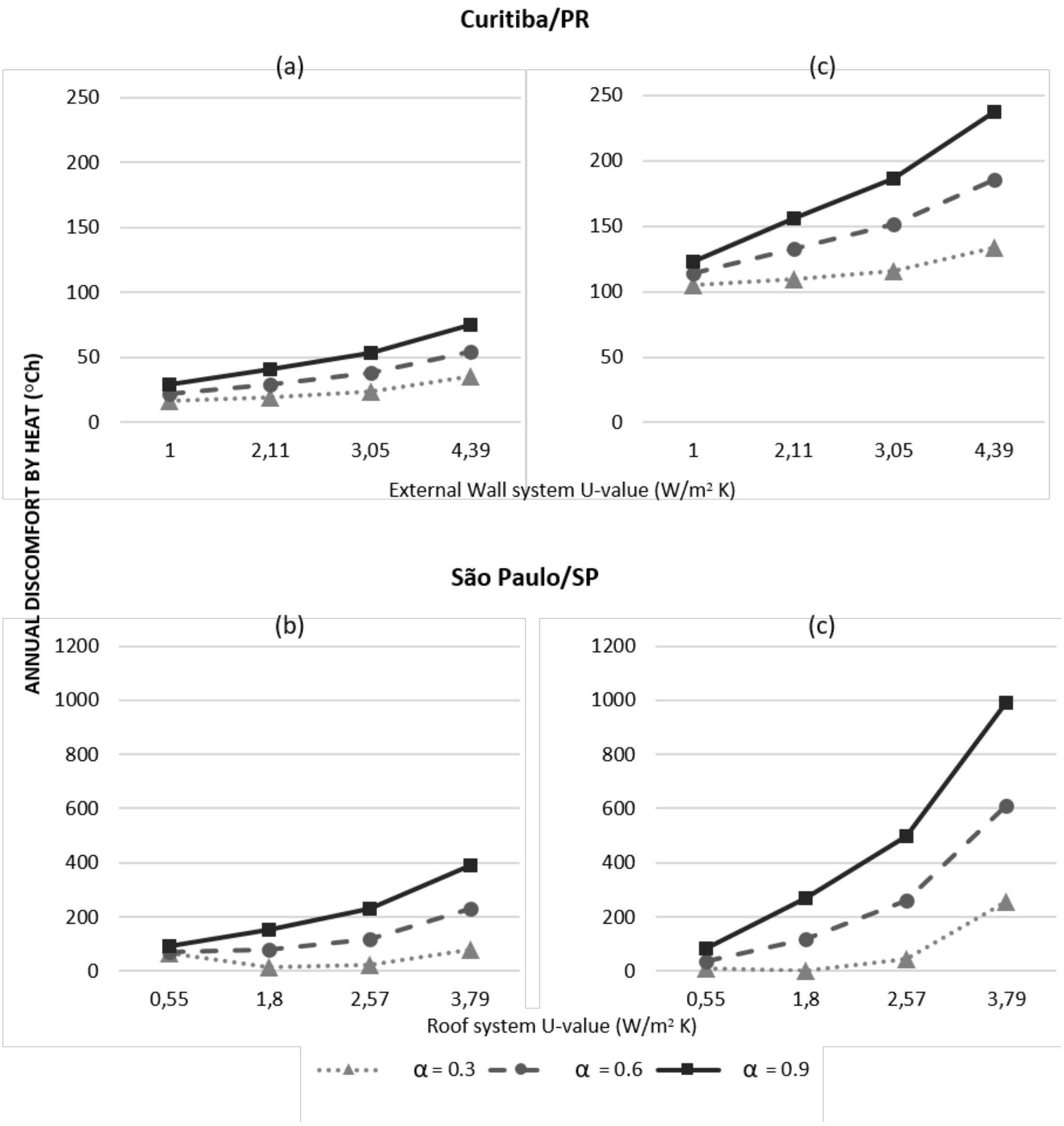


Figure 31: Heat discomfort predicted for cases 1 to 12 in São Paulo and cases 13 to 24 in Curitiba with the standard ("a" and "b") and NZ ("c" and "d") meta-models.

Figure 30 and *Figure 31* show that the increase of α is associated with a decrease of the discomfort by cold and an increase of the discomfort by heat. Therefore, climates peculiarities must be investigated before deciding whether a low or high absorptance (α) must be used, depending on their needs to prevent from cold and heat. Also, higher OE U-values indicate more discomfort; however it is important to consider the U-value and α conjugated.

Walls and roof systems more insulated (low U-values) are less impacted by the α; e.g. the higher U-values considered show significant differences in the discomfort predicted for each value of α, and these differences are diminished with the U-value decrease.

The results show compliance to thermal behavior that was expected according to the information collected from the literature review, especially in Chvatal (2014) that used

EnergyPlus simulations to assess the thermal performance of Brazilian LCHs and obtained quite similar results.

Figure 31 highlights the difference of predictions between the Curitiba and São Paulo standard and NZ heat discomfort models, and confirms what was discussed above in item 5.3. REGRESSION RESULTS AND VALIDATION. Great discrepancies of the results are found between the two models, and the NZ models always report higher discomfort levels.

The potentiality of the meta-models to guide designers during the early design could be confirmed for Curitiba and São Paulo cold discomfort models, and Manaus heat discomfort model; they allow a fast and accurate assessment of the LCH thermal performance in response to the input of group of information.

Despite of the attempts to improve the accuracy of the heat discomfort models for Curitiba and São Paulo their fit to the results that would be predicted based on the EnergyPlus output is unsure; Therefore, the use of these models are not recommended.

6. CONCLUSIONS

This research fills a gap in the existing literature by developing a set of regression models that may be used to predict the heat and cold degree hours of discomfort inside of a naturally ventilated low-cost house in three Brazilian cities: Curitiba/PR, São Paulo/SP, and Manaus/AM. It was motivated by the lack of thermal performance quantitative information available to guide the designer decision-making during the early stages of building design. The generated regression models consider the variation of three important building opaque envelope thermal physical properties: U-value, heat capacity and solar absorptance. Also, due to a partnership with other researchers parameters related to natural ventilation and shading devices are also considered. From the total of terms added to each regression model, more than sixty percent are directly related to the building envelope properties parameters, indicating the great importance of this element in the thermal comfort of this type of building.

A detached pitched roof single-family low-cost house unit with no ventilated attic and with a rectangular shape floor plan area of about $50m^2$ divided into a combined living room and kitchen, two bedrooms, and a bathroom is considered. A set of usual low-cost house design underlies the development of the considered geometry, so it spans the usual Brazilian construction. A single zone modeling approach was used based on an extensive set of tests which demonstrate that for the considered model no significant prediction differences were found between the multi-zone and single-zone modeling approach. The EnergyPlus material and construction input data method was simplified by the development of virtual materials that compose virtual walls and roof system constructions. This simplification method was extensively tested and shows good accuracy. Detailed regression analyses are used to improve the regression model accuracy; six analysis procedures are applied according to each regression peculiarity.

The regression models to predict cold discomfort for São Paulo and Curitiba and heat discomfort for Manaus show R^2 values superior to 0.95 indicating accurate predictions when compared to the discomfort predicted based on the output data from EnergyPlus, the original simulation software. Due to such accuracy, the regression models obtained allow designers to quickly access, in the early design stage, the building thermal performance from a range of design alternatives.

The heat discomfort models for São Paulo and Curitiba show R^2 inferior to 0.75 and as an attempt to improve the models fit a non-zero approach were performed. The non-zero models show good fits (R^2 superior to 0.83) when validated with no-zero values only, but their R^2 are drastically dropped to less than 0.4 when validated with the whole validation set (40%

of the 10,000 simulations). Therefore, non-zero models can accurate predict the cases that the EnergyPlus outputs show heat discomfort, but they are not able to indicate that some key design parameter combinations result in no levels of heat discomfort. Also, selecting only the cases that reported some levels of heat discomfort may have compromised the randomness of the samples.

The meta-models guidance potential was confirmed by a meta-model application test that assessed the conjugated impact of the external walls ad roof system thermo-physical properties (U-value, HC, and α).

It is important to highlight that the regression model prediction ability is limited to the characteristics considered during the development of the model, such as location, building type, building size, among others.

6.1. FURTHER WORK

To implement and expand the use of regression models to guide the design process further work may be developed to generalize the models, to enlarge the number of parameters considered, and to allow different kind of analysis. The model generalization may encompass variations on building shape, size, location, and type. New parameters may be included in the model: building envelope dynamic thermal properties; a ventilated attic; exterior landscape elements such as walls, trees, and other elements of the surrounding area; etc. Different kinds of analysis may be included, as the number of air changes per hour, energy consumption in the cases that artificial conditioning may apply, among others.

Also, it is necessary to expand the investigations to validate the information used as the input data for the simulations in the robust software, such as the ground temperature, because this modeling detail has a great impact on the simulation results even for simple buildings as the LCHs.

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APPENDIX 01- Curitiba/PR: Meta-model coefficients – Degree-hours of discomfort by cold (standard approach with regression floor)

Coefficient	Meaning	value	p-value
INTERCEPT	INTERCEPT	18385,64	3,6E-116
x4	External Walls' Solar Absorptance	-2756,91	1,13E-28
x5	Bedroom_1 Left Fin size	494,6549	5,78E-06
x6	Bedroom_2 Left Fin size	3175,784	1,3E-09
x7	Living room Left Fin size	3386,239	3,22E-07
x8	Bedroom_1 Right Fin size	-327,328	0,067332
x9	Bedroom_2 Right Fin size	-3608,49	2,48E-07
x10	Living room Right Fin size	226,1234	0,293776
x11	Bedroom_1 Overhang size	3096,869	1,68E-05
x12	Bedroom_2 Overhang size	2787,848	4,28E-09
x13	Living room Overhang size	-2377,56	1,85E-07
x14	Roof's Solar Absorptance	-4334,19	1,33E-44
x15	North Axis/ Orientation in the terrain	-20,7409	8,66E-76
x16	Bedroom_1 Window to Wall Ratio (WWR)	-961,52	0,001007
x17	Bedroom_2 Window to Wall Ratio (WWR)	-7686,31	2,33E-17
x18	Living room Window to Wall Ratio (WWR)	-1599,12	3,21E-09
x19	External Walls' U-value	2666,385	2,5E-258
x21	Roof's U-Value	2865,937	6,31E-30
x22	External Walls' Heat Capacity	-6,96385	5,64E-14
x23	Internal Walls' Heat Capacity	-11,8464	2,61E-15
x24	Roof's Heat Capacity	-6,50643	1,52E-10
x39	Inverse of North Axis/ Orientation in the terrain	-1301,22	0,005534
x41	Inverse of Bedroom_2 Window to Wall Ratio (WWR)	-1007,71	1,96E-20
x47	Inverse of Internal Walls' Heat Capacity	-443728	9,36E-29
x48	Inverse of Roof's Heat Capacity	-230452	1,49E-35
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	723,4714	1,54E-08
x4:x16	External Walls' Solar Absorptance x Bedroom_1 Window to Wall Ratio (WWR)	757,6435	0,000148
x4:x17	External Walls' Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	707,6947	0,000482
x4:x18	External Walls' Solar Absorptance x Living room Window to Wall Ratio (WWR)	690,4265	0,000597
x4:x19	External Walls' Solar Absorptance x External Walls' U-value	-1583,65	0

x4:x22	External Walls' Solar Absorptance x External Walls' Heat Capacity	-1,39113	8,01E-07
x5:x39	Bedroom_1 Left Fin size x Inverse of North Axis/ Orientation in the terrain	-1563,43	0,001514
x5:x47	Bedroom_1 Left Fin size x Inverse of Internal Walls' Heat Capacity	-31719,7	0,014659
x5:x48	Bedroom_1 Left Fin size x Inverse of Roof's Heat Capacity	-16085,7	0,029741
x6:x21	Bedroom_2 Left Fin size x Roof's U-Value	-303,979	0,035609
x6:x22	Bedroom_2 Left Fin size x External Walls' Heat Capacity	-0,99393	0,047843
x6:x23	Bedroom_2 Left Fin size x Internal Walls' Heat Capacity	-2,11604	0,021566
x6:x24	Bedroom_2 Left Fin size x Roof's Heat Capacity	-1,34206	0,007808
x6:x41	Bedroom_2 Left Fin size x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	-144,855	0,000942
x6:x47	Bedroom_2 Left Fin size x Inverse of Internal Walls' Heat Capacity	-80661,8	0,000824
x6:x48	Bedroom_2 Left Fin size x Inverse of Roof's Heat Capacity	-35746,7	0,000284
x7:x15	Living room Left Fin size x North Axis/ Orientation in the terrain	-1,28118	0,02376
x7:x17	Living room Left Fin size x Bedroom_2 Window to Wall Ratio (WWR)	-1550,29	0,037601
x7:x23	Living room Left Fin size x Internal Walls' Heat Capacity	-2,85755	0,001871
x7:x41	Living room Left Fin size x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	-275,727	0,001711
x7:x47	Living room Left Fin size x Inverse of Internal Walls' Heat Capacity	-113778	2,43E-06
x7:x48	Living room Left Fin size x Inverse of Roof's Heat Capacity	-38033,9	6,44E-07
x8:x15	Bedroom_1 Right Fin size x North Axis/ Orientation in the terrain	1,251773	0,031419
x8:x39	Bedroom_1 Right Fin size x Inverse of North Axis/ Orientation in the terrain	1187,851	0,002657
x8:x41	Bedroom_1 Right Fin size x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	94,34965	0,033376
x8:x48	Bedroom_1 Right Fin size x Inverse of Roof's Heat Capacity	13754,79	0,064254
x9:x15	Bedroom_2 Right Fin size x North Axis/ Orientation in the terrain	1,673533	0,003022
x9:x17	Bedroom_2 Right Fin size x Bedroom_2 Window to Wall Ratio (WWR)	2434,638	0,001283

x9:x23	Bedroom_2 Right Fin size x Internal Walls' Heat Capacity	1,85362	0,040696
x9:x24	Bedroom_2 Right Fin size x Roof's Heat Capacity	0,969698	0,048982
x9:x41	Bedroom_2 Right Fin size x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	350,1333	0,000117
x9:x47	Bedroom_2 Right Fin size x Inverse of Internal Walls' Heat Capacity	83029,7	0,000513
x9:x48	Bedroom_2 Right Fin size x Inverse of Roof's Heat Capacity	51610,01	4,08E-08
x10:x14	Living room Right Fin size x Roof's Solar Absorptance	-513,735	0,025839
x10:x18	Living room Right Fin size x Living room Window to Wall Ratio (WWR)	800,5204	0,028759
x10:x48	Living room Right Fin size x Inverse of Roof's Heat Capacity	-16831,5	0,02117
x11:x12	Bedroom_1 Overhang size x Bedroom_2 Overhang size	795,0845	0,05541
x11:x14	Bedroom_1 Overhang size x Roof's Solar Absorptance	-504,148	0,028374
x11:x15	Bedroom_1 Overhang size x North Axis/ Orientation in the terrain	1,342506	0,017342
x11:x16	Bedroom_1 Overhang size x Bedroom_1 Window to Wall Ratio (WWR)	997,7483	0,005321
x11:x17	Bedroom_1 Overhang size x Bedroom_2 Window to Wall Ratio (WWR)	-1696,94	0,024549
x11:x19	Bedroom_1 Overhang size x External Walls' U-value	-284,195	5,88E-05
x11:x21	Bedroom_1 Overhang size x Roof's U-Value	-339,883	0,017539
x11:x23	Bedroom_1 Overhang size x Internal Walls' Heat Capacity	-2,1717	0,015469
x11:x41	Bedroom_1 Overhang size x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	-263,338	0,003379
x11:x47	Bedroom_1 Overhang size x Inverse of Internal Walls' Heat Capacity	-88473,9	0,00013
x11:x48	Bedroom_1 Overhang size x Inverse of Roof's Heat Capacity	-24077,2	0,000588
x12:x14	Bedroom_2 Overhang size x Roof's Solar Absorptance	-565,314	0,014674
x12:x15	Bedroom_2 Overhang size x North Axis/ Orientation in the terrain	-1,17053	0,042024
x12:x17	Bedroom_2 Overhang size x Bedroom_2 Window to Wall Ratio (WWR)	2037,285	1,94E-08
x12:x19	Bedroom_2 Overhang size x External Walls' U-value	-222,394	0,001945
x12:x23	Bedroom_2 Overhang size x Internal Walls' Heat Capacity	-3,56782	0,000113

x12:x24	Bedroom_2 Overhang size x Roof's Heat Capacity	-1,41959	0,004281
x12:x39	Bedroom_2 Overhang size x Inverse of North Axis/ Orientation in the terrain	-1458,48	0,002236
x12:x47	Bedroom_2 Overhang size x Inverse of Internal Walls' Heat Capacity	-151988	3,36E-10
x12:x48	Bedroom_2 Overhang size x Inverse of Roof's Heat Capacity	-71942,7	4,89E-14
x13:x18	Living room Overhang size x Living room Window to Wall Ratio (WWR)	1118,148	0,002388
x13:x23	Living room Overhang size x Internal Walls' Heat Capacity	2,554241	0,006229
x13:x24	Living room Overhang size x Roof's Heat Capacity	1,539743	0,002327
x13:x41	Living room Overhang size x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	131,2863	0,002459
x13:x47	Living room Overhang size x Inverse of Internal Walls' Heat Capacity	100816,1	4,2E-05
x13:x48	Living room Overhang size x Inverse of Roof's Heat Capacity	68930,95	4,81E-13
x14:x15	Roof's Solar Absorptance x North Axis/ Orientation in the terrain	1,062143	0,000999
x14:x18	Roof's Solar Absorptance x Living room Window to Wall Ratio (WWR)	471,3394	0,01923
x14:x19	Roof's Solar Absorptance x External Walls' U-value	498,219	2,26E-39
x14:x21	Roof's Solar Absorptance x Roof's U-Value	-3651,43	0
x14:x23	Roof's Solar Absorptance x Internal Walls' Heat Capacity	2,057037	5,73E-05
x14:x39	Roof's Solar Absorptance x Inverse of North Axis/ Orientation in the terrain	1107,284	6E-06
x14:x47	Roof's Solar Absorptance x Inverse of Internal Walls' Heat Capacity	87494,02	2,22E-11
x14:x48	Roof's Solar Absorptance x Inverse of Roof's Heat Capacity	59679,53	2,35E-49
x15:x16	North Axis/ Orientation in the terrain x Bedroom_1 Window to Wall Ratio (WWR)	-4,17904	3,78E-17
x15:x17	North Axis/ Orientation in the terrain x Bedroom_2 Window to Wall Ratio (WWR)	2,284073	0,029372
x15:x19	North Axis/ Orientation in the terrain x External Walls' U-value	0,266389	0,009415
x15:x21	North Axis/ Orientation in the terrain x Roof's U-Value	0,474984	0,019096
x15:x23	North Axis/ Orientation in the terrain x Internal Walls' Heat Capacity	0,00519	3,53E-05
x15:x24	North Axis/ Orientation in the terrain x Roof's Heat Capacity	0,002092	0,002756

x15:x41	North Axis/ Orientation in the terrain x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	0,467003	0,000214
x15:x47	North Axis/ Orientation in the terrain x Inverse of Internal Walls' Heat Capacity	190,3256	6,42E-09
x15:x48	North Axis/ Orientation in the terrain x Inverse of Roof's Heat Capacity	100,1104	2,34E-13
x16:x17	Bedroom_1 Window to Wall Ratio (WWR) x Bedroom_2 Window to Wall Ratio (WWR)	1048,579	0,000712
x16:x18	Bedroom_1 Window to Wall Ratio (WWR) x Living room Window to Wall Ratio (WWR)	647,0496	0,042999
x16:x19	Bedroom_1 Window to Wall Ratio (WWR) x External Walls' U-value	-130,306	0,0379
x16:x22	Bedroom_1 Window to Wall Ratio (WWR) x External Walls' Heat Capacity	-0,93141	0,035377
x17:x21	Bedroom_2 Window to Wall Ratio (WWR) x Roof's U-Value	725,1015	0,006219
x17:x22	Bedroom_2 Window to Wall Ratio (WWR) x External Walls' Heat Capacity	2,104073	0,021782
x17:x23	Bedroom_2 Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	6,28843	0,00013
x17:x24	Bedroom_2 Window to Wall Ratio (WWR) x Roof's Heat Capacity	2,351353	0,009602
x17:x47	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Internal Walls' Heat Capacity	233910,8	1,08E-08
x17:x48	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	127327,5	3,93E-12
x18:x39	Living room Window to Wall Ratio (WWR) x Inverse of North Axis/ Orientation in the terrain	1813,6	0,000292
x18:x41	Living room Window to Wall Ratio (WWR) x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	-194,491	3,26E-07
x19:x21	External Walls' U-value x Roof's U-Value	-218,549	6,88E-20
x19:x22	External Walls' U-value x External Walls' Heat Capacity	-0,69686	1,66E-16
x19:x24	External Walls' U-value x Roof's Heat Capacity	-0,16906	0,040065
x19:x39	External Walls' U-value x Inverse of North Axis/ Orientation in the terrain	-668,837	0,000175
x19:x41	External Walls' U-value x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	27,2388	9,63E-05
x19:x47	External Walls' U-value x Inverse of Internal Walls' Heat Capacity	13754,08	1,04E-09
x19:x48	External Walls' U-value x Inverse of Roof's Heat Capacity	5654,901	3,6E-05
x21:x23	Roof's U-Value x Internal Walls' Heat Capacity	0,812822	0,00934
x21:x24	Roof's U-Value x Roof's Heat Capacity	-0,42091	0,01508

x21:x39	Roof's U-Value x Inverse of North Axis/ Orientation in the terrain	-280,024	0,018208
x21:x41	Roof's U-Value x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	121,9251	0,000127
x21:x47	Roof's U-Value x Inverse of Internal Walls' Heat Capacity	44061,9	4,34E-08
x21:x48	Roof's U-Value x Inverse of Roof's Heat Capacity	22642,77	8,18E-13
x22:x23	External Walls' Heat Capacity x Internal Walls' Heat Capacity	0,003632	0,000994
x22:x24	External Walls' Heat Capacity x Roof's Heat Capacity	0,003173	2,25E-12
x22:x41	External Walls' Heat Capacity x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	0,419161	0,00011
x22:x47	External Walls' Heat Capacity x Inverse of Internal Walls' Heat Capacity	72,54738	0,012133
x23:x24	Internal Walls' Heat Capacity x Roof's Heat Capacity	0,004758	1,26E-05
x23:x41	Internal Walls' Heat Capacity x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	1,223949	2,32E-10
x23:x48	Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	186,8037	1,32E-19
x24:x39	Roof's Heat Capacity x Inverse of North Axis/ Orientation in the terrain	-0,8409	0,065167
x24:x41	Roof's Heat Capacity x Inverse of Bedroom_2 Window to Wall Ratio (WWR)	0,404944	0,000146
x24:x47	Roof's Heat Capacity x Inverse of Internal Walls' Heat Capacity	151,6058	9,22E-08
x41:x47	Inverse of Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Internal Walls' Heat Capacity	46847,78	1,12E-22
x41:x48	Inverse of Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	21864,94	2,67E-24
x47:x48	Inverse of Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	8761530	1,16E-59
x4^2	External Walls' Solar Absorptance^2	527,8405	0,000248
x6^2	Bedroom_2 Left Fin size^2	-941,356	0,043109
x14^2	Roof's Solar Absorptance^2	1404,531	9,52E-23
x15^2	North Axis/ Orientation in the terrain^2	0,036833	3,6E-304
x19^2	External Walls' U-value^2	-109,712	1,4E-43
x22^2	External Walls' Heat Capacity^2	0,005532	5,52E-16
x24^2	Roof's Heat Capacity^2	0,001443	0,037068
x39^2	Inverse of North Axis/ Orientation in the terrain^2	148,4513	1,64E-14
x47^2	Inverse of Internal Walls' Heat Capacity^2	1778989	0,001615
x48^2	Inverse of Roof's Heat Capacity^2	-483967	3,11E-05

APPENDIX 02 - Curitiba/PR: Meta-model coefficients – Degree-hours of discomfort by heat (standard approach with regression floor)

Coefficient	Meaning	value	p-value
INTERCEPT	INTERCEPT	56,21201	0,003227
x3	Living room Effective window ventilation area	90,89477	3,48E-08
x4	External Walls' Solar Absorptance	-58,35	5,75E-09
x13	Living room Overhang size	103,5655	9,66E-10
x14	Roof's Solar Absorptance	-157,764	1,57E-54
x18	Living room Window to Wall Ratio (WWR)	-5,06523	0,205875
x19	External Walls' U-value	-18,3262	2,11E-44
x21	Roof's U-Value	-59,9842	3,2E-07
x24	Roof's Heat Capacity	0,203004	6,31E-23
x45	Inverse of Roof's U-Value	-9,31795	0,248669
x46	Inverse of External Walls' Heat Capacity	-5744,54	1E-22
x47	Inverse of Internal Walls' Heat Capacity	-3347,65	8,56E-09
x48	Inverse of Roof's Heat Capacity	-1980,84	7,37E-07
x3:x21	Living room Effective window ventilation area x Roof's U-Value	-49,0604	5,48E-10
x3:x45	Living room Effective window ventilation area x Inverse of Roof's U-Value	-30,8972	2,63E-05
x3:x46	Living room Effective window ventilation area x Inverse of External Walls' Heat Capacity	-972,667	0,00025
x3:x47	Living room Effective window ventilation area x Inverse of Internal Walls' Heat Capacity	-617,76	0,018928
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	11,1276	2,1E-05
x4:x19	External Walls' Solar Absorptance x External Walls' U-value	13,62601	3,05E-65
x4:x21	External Walls' Solar Absorptance x Roof's U-Value	20,73743	3,07E-06
x4:x24	External Walls' Solar Absorptance x Roof's Heat Capacity	-0,02653	3,76E-10
x4:x45	External Walls' Solar Absorptance x Inverse of Roof's U-Value	12,41491	0,002711
x4:x46	External Walls' Solar Absorptance x Inverse of External Walls' Heat Capacity	1323,415	6,63E-19
x4:x47	External Walls' Solar Absorptance x Inverse of Internal Walls' Heat Capacity	397,254	0,009521
x13:x14	Living room Overhang size x Roof's Solar Absorptance	-15,1162	0,00146
x13:x21	Living room Overhang size x Roof's U-Value	-50,0336	4,91E-10

x13:x45	Living room Overhang size x Inverse of Roof's U-Value	-30,3248	6,26E-05
x13:x46	Living room Overhang size x Inverse of External Walls' Heat Capacity	-1100,82	2,66E-05
x13:x47	Living room Overhang size x Inverse of Internal Walls' Heat Capacity	-1045,1	0,000123
x13:x48	Living room Overhang size x Inverse of Roof's Heat Capacity	-375,549	0,00856
x14:x19	Roof's Solar Absorptance x External Walls' U-value	4,912302	1,62E-10
x14:x21	Roof's Solar Absorptance x Roof's U-Value	75,7089	2,74E-65
x14:x24	Roof's Solar Absorptance x Roof's Heat Capacity	-0,02123	0,000188
x14:x45	Roof's Solar Absorptance x Inverse of Roof's U-Value	40,51501	1,66E-22
x14:x46	Roof's Solar Absorptance x Inverse of External Walls' Heat Capacity	1773,623	6,39E-34
x14:x47	Roof's Solar Absorptance x Inverse of Internal Walls' Heat Capacity	925,5288	5,65E-10
x14:x48	Roof's Solar Absorptance x Inverse of Roof's Heat Capacity	1433,689	5,55E-39
x18:x19	Living room Window to Wall Ratio (WWR) x External Walls' U-value	3,131024	0,013169
x18:x21	Living room Window to Wall Ratio (WWR) x Roof's U-Value	6,445681	0,014365
x18:x24	Living room Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,03225	1,15E-06
x18:x46	Living room Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	896,7809	0,000131
x18:x47	Living room Window to Wall Ratio (WWR) x Inverse of Internal Walls' Heat Capacity	682,4573	0,00453
x19:x21	External Walls' U-value x Roof's U-Value	1,579005	0,001159
x19:x24	External Walls' U-value x Roof's Heat Capacity	-0,01408	4,74E-17
x19:x46	External Walls' U-value x Inverse of External Walls' Heat Capacity	845,1039	3,41E-80
x19:x47	External Walls' U-value x Inverse of Internal Walls' Heat Capacity	309,437	1,17E-11
x19:x48	External Walls' U-value x Inverse of Roof's Heat Capacity	62,09573	0,022655
x21:x24	Roof's U-Value x Roof's Heat Capacity	-0,07346	2,43E-14
x21:x46	Roof's U-Value x Inverse of External Walls' Heat Capacity	2721,857	2,57E-28
x21:x47	Roof's U-Value x Inverse of Internal Walls' Heat Capacity	1794,206	1,2E-12
x21:x48	Roof's U-Value x Inverse of Roof's Heat Capacity	1372,534	2,08E-14
x24:x45	Roof's Heat Capacity x Inverse of Roof's U-Value	-0,04596	2,72E-07

x24:x46	Roof's Heat Capacity x Inverse of External Walls' Heat Capacity	-1,96853	1,33E-09
x24:x47	Roof's Heat Capacity x Inverse of Internal Walls' Heat Capacity	-1,36258	2,27E-05
x45:x46	Inverse of Roof's U-Value x Inverse of External Walls' Heat Capacity	1323,99	2,01E-08
x45:x47	Inverse of Roof's U-Value x Inverse of Internal Walls' Heat Capacity	865,682	0,000234
x45:x48	Inverse of Roof's U-Value x Inverse of Roof's Heat Capacity	515,4849	0,002303
x46:x47	Inverse of External Walls' Heat Capacity x Inverse of Internal Walls' Heat Capacity	96581,18	9,64E-30
x46:x48	Inverse of External Walls' Heat Capacity x Inverse of Roof's Heat Capacity	57558,36	4,23E-21
x47:x48	Inverse of Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	24868,09	3,91E-05
x4^2	External Walls' Solar Absorptance^2	7,359847	0,012301
x14^2	Roof's Solar Absorptance^2	18,52881	1,94E-10
x19^2	External Walls' U-value^2	1,641649	2,12E-24
x21^2	Roof's U-Value^2	16,13522	5,97E-10
x48^2	Inverse of Roof's Heat Capacity^2	-17056,6	4,48E-24

APPENDIX 03 - Curitiba/PR: Meta-model coefficients – Degree-hours of discomfort by heat (Non-zero approach with regression floor)

Coefficient	**Meaning**	**value**	**p-value**
INTERCEPT	INTERCEPT	358,3747	3,02E-12
x4	External Walls' Solar Absorptance	-176,567	5,93E-18
x9	Bedroom_2 Right Fin size	-52,0469	0,000224
x11	Bedroom_1 Overhang size	-8,72256	0,035275
x12	Bedroom_2 Overhang size	-2,7608	0,844729
x13	Living room Overhang size	45,81751	0,000384
x14	Roof's Solar Absorptance	-336,754	3,26E-12
x16	Bedroom_1 Window to Wall Ratio (WWR)	47,6327	0,000125
x17	Bedroom_2 Window to Wall Ratio (WWR)	-14,7976	0,214369
x18	Living room Window to Wall Ratio (WWR)	26,97337	0,001166
x19	External Walls' U-value	-44,9846	1,21E-13
x21	Roof's U-Value	-249,298	6,01E-14
x22	External Walls' Heat Capacity	0,004138	0,951917
x24	Roof's Heat Capacity	0,586081	1,33E-16
x30	Inverse of Bedroom_2 Left Fin size	-0,07762	0,812395
x43	Inverse of External Walls' U-value	-6,28239	0,166167
x45	Inverse of Roof's U-Value	-59,1857	0,000447
x46	Inverse of External Walls' Heat Capacity	-14492,7	4,43E-14
x47	Inverse of Internal Walls' Heat Capacity	-6040,44	2,4E-10
x4:x12	External Walls' Solar Absorptance x Bedroom_2 Overhang size	-42,2659	0,017261
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	92,14922	3,08E-10
x4:x17	External Walls' Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	31,99793	0,036676
x4:x19	External Walls' Solar Absorptance x External Walls' U-value	41,88045	1,48E-56
x4:x21	External Walls' Solar Absorptance x Roof's U-Value	52,73584	2,29E-19
x4:x24	External Walls' Solar Absorptance x Roof's Heat Capacity	-0,21619	6,66E-24
x4:x46	External Walls' Solar Absorptance x Inverse of External Walls' Heat Capacity	5883,885	1,23E-29
x4:x47	External Walls' Solar Absorptance x Inverse of Internal Walls' Heat Capacity	2729,927	2,68E-07
x9:x14	Bedroom_2 Right Fin size x Roof's Solar Absorptance	42,82548	0,019203
x9:x24	Bedroom_2 Right Fin size x Roof's Heat Capacity	0,065345	0,020128

x12:x43	Bedroom_2 Overhang size x Inverse of External Walls' U-value	10,66446	0,021182
x13:x21	Living room Overhang size x Roof's U-Value	-34,7	5,53E-05
x13:x47	Living room Overhang size x Inverse of Internal Walls' Heat Capacity	-2777,92	0,001667
x14:x16	Roof's Solar Absorptance x Bedroom_1 Window to Wall Ratio (WWR)	-50,6403	0,001423
x14:x19	Roof's Solar Absorptance x External Walls' U-value	18,58297	7,43E-11
x14:x21	Roof's Solar Absorptance x Roof's U-Value	191,2808	1,26E-30
x14:x22	Roof's Solar Absorptance x External Walls' Heat Capacity	-0,15364	0,004051
x14:x24	Roof's Solar Absorptance x Roof's Heat Capacity	-0,29456	2,21E-35
x14:x45	Roof's Solar Absorptance x Inverse of Roof's U-Value	56,254	0,000841
x14:x46	Roof's Solar Absorptance x Inverse of External Walls' Heat Capacity	3868,094	7,04E-05
x14:x47	Roof's Solar Absorptance x Inverse of Internal Walls' Heat Capacity	3724,52	4,84E-10
x16:x43	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of External Walls' U-value	12,93459	0,001122
x16:x47	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of Internal Walls' Heat Capacity	-2115,81	0,005263
x17:x46	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	1987,836	0,004038
x18:x24	Living room Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,07456	0,002555
x18:x30	Living room Window to Wall Ratio (WWR) x Inverse of Bedroom_2 Left Fin size	-1,25358	0,002534
x18:x46	Living room Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	2890,185	6,53E-05
x19:x21	External Walls' U-value x Roof's U-Value	7,855186	3,9E-05
x19:x22	External Walls' U-value x External Walls' Heat Capacity	-0,05341	3,69E-08
x19:x24	External Walls' U-value x Roof's Heat Capacity	-0,06174	2,8E-41
x19:x46	External Walls' U-value x Inverse of External Walls' Heat Capacity	1038,687	2,14E-07
x19:x47	External Walls' U-value x Inverse of Internal Walls' Heat Capacity	1171,907	1,12E-20
x21:x22	Roof's U-Value x External Walls' Heat Capacity	-0,08	0,000884
x21:x24	Roof's U-Value x Roof's Heat Capacity	-0,31627	3,4E-38
x21:x30	Roof's U-Value x Inverse of Bedroom_2 Left Fin size	0,541511	7,41E-06
x21:x43	Roof's U-Value x Inverse of External Walls' U-value	-5,0214	0,032584
x21:x46	Roof's U-Value x Inverse of External Walls' Heat	4088,617	5,32E-07

	Capacity		
x21:x47	Roof's U-Value x Inverse of Internal Walls' Heat Capacity	3164,67	7,07E-29
x22:x24	External Walls' Heat Capacity x Roof's Heat Capacity	0,000571	1,7E-13
x24:x30	Roof's Heat Capacity x Inverse of Bedroom_2 Left Fin size	-0,00124	0,000751
x24:x45	Roof's Heat Capacity x Inverse of Roof's U-Value	-0,10499	7,38E-05
x24:x46	Roof's Heat Capacity x Inverse of External Walls' Heat Capacity	-6,61937	6,33E-06
x24:x47	Roof's Heat Capacity x Inverse of Internal Walls' Heat Capacity	-11,3061	1,69E-32
x30:x47	Inverse of Bedroom_2 Left Fin size x Inverse of Internal Walls' Heat Capacity	26,18306	0,028809
x45:x46	Inverse of Roof's U-Value x Inverse of External Walls' Heat Capacity	1511,287	0,046572
x46:x47	Inverse of External Walls' Heat Capacity x Inverse of Internal Walls' Heat Capacity	225123,5	6,97E-20
x14^2	Roof's Solar Absorptance^2	62,80359	2,98E-06
x19^2	External Walls' U-value^2	3,785869	4,54E-08
x21^2	Roof's U-Value^2	47,31777	1,5E-09
x22^2	External Walls' Heat Capacity^2	0,000288	0,004714
x24^2	Roof's Heat Capacity^2	0,000526	6,42E-59
x30^2	Inverse of Bedroom_2 Left Fin size^2	0,005166	0,017999

APPENDIX 04 - São Paulo/SP: Meta-model coefficients – Degree-hours of discomfort by cold (standard approach with regression floor)

Coefficient	Meaning	value	p-value
INTERCEPT	INTERCEPT	3492,212	0
x4	External Walls' Solar Absorptance	-1805,7	2,9E-149
x5	Bedroom_1 Left Fin size	150,607	0,001339
x6	Bedroom_2 Left Fin size	181,8468	0,004163
x7	Living room Left Fin size	-4,07676	0,937628
x8	Bedroom_1 Right Fin size	-17,1501	0,538154
x9	Bedroom_2 Right Fin size	-47,8172	0,361285
x10	Living room Right Fin size	71,5257	0,254192
x11	Bedroom_1 Overhang size	313,6652	6,55E-06
x12	Bedroom_2 Overhang size	170,6565	0,000175
x13	Living room Overhang size	381,4572	6,05E-08
x14	Roof's Solar Absorptance	-1626,23	6,7E-129
x15	North Axis/ Orientation in the terrain	-8,43494	0
x17	Bedroom_2 Window to Wall Ratio (WWR)	-612,262	1,42E-15
x18	Living room Window to Wall Ratio (WWR)	-750,439	3,58E-28
x19	External Walls' U-value	1896,31	0
x21	Roof's U-Value	2671,813	0
x22	External Walls' Heat Capacity	-2,76346	1,28E-45
x23	Internal Walls' Heat Capacity	-0,82868	2,56E-12
x24	Roof's Heat Capacity	-1,04491	1,15E-10
x35	Inverse of Bedroom_1 Overhang size	0,968856	6,95E-07
x39	Inverse of North Axis/ Orientation in the terrain	-829,156	5,65E-10
x40	Inverse of Bedroom_1 Window to Wall Ratio (WWR)	82,86173	5,41E-15
x46	Inverse of External Walls' Heat Capacity	-5027,45	0,119784
x48	Inverse of Roof's Heat Capacity	7326,963	0,000656
x4:x11	External Walls' Solar Absorptance x Bedroom_1 Overhang size	-115,734	0,022153
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	797,5468	1,4E-167
x4:x15	External Walls' Solar Absorptance x North Axis/ Orientation in the terrain	0,333428	1,58E-06
x4:x17	External Walls' Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	424,3361	3,6E-22
x4:x18	External Walls' Solar Absorptance x Living room Window to Wall Ratio (WWR)	401,2784	5,98E-21

x4:x19	External Walls' Solar Absorptance x External Walls' U-value	-930,732	0
x4:x21	External Walls' Solar Absorptance x Roof's U-Value	-45,8067	0,007676
x4:x22	External Walls' Solar Absorptance x External Walls' Heat Capacity	-0,24648	0,024791
x4:x40	External Walls' Solar Absorptance x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	-43,0326	5,39E-17
x4:x46	External Walls' Solar Absorptance x Inverse of External Walls' Heat Capacity	12010,35	2,15E-05
x5:x6	Bedroom_1 Left Fin size x Bedroom_2 Left Fin size	195,6862	0,037671
x5:x14	Bedroom_1 Left Fin size x Roof's Solar Absorptance	-121,834	0,016785
x5:x40	Bedroom_1 Left Fin size x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	-19,052	0,043601
x6:x7	Bedroom_2 Left Fin size x Living room Left Fin size	-202,7	0,029376
x6:x14	Bedroom_2 Left Fin size x Roof's Solar Absorptance	-140,855	0,005356
x6:x15	Bedroom_2 Left Fin size x North Axis/ Orientation in the terrain	-0,4445	0,000615
x6:x17	Bedroom_2 Left Fin size x Bedroom_2 Window to Wall Ratio (WWR)	242,9577	0,002577
x6:x39	Bedroom_2 Left Fin size x Inverse of North Axis/ Orientation in the terrain	-801,063	7,8E-10
x7:x18	Living room Left Fin size x Living room Window to Wall Ratio (WWR)	190,2675	0,015741
x7:x21	Living room Left Fin size x Roof's U-Value	58,86032	0,057451
x8:x15	Bedroom_1 Right Fin size x North Axis/ Orientation in the terrain	0,493053	0,000154
x8:x39	Bedroom_1 Right Fin size x Inverse of North Axis/ Orientation in the terrain	628,9143	0,000139
x9:x14	Bedroom_2 Right Fin size x Roof's Solar Absorptance	-99,0826	0,049068
x9:x17	Bedroom_2 Right Fin size x Bedroom_2 Window to Wall Ratio (WWR)	292,7451	0,000188
x9:x40	Bedroom_2 Right Fin size x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	24,63209	0,00857
x10:x18	Living room Right Fin size x Living room Window to Wall Ratio (WWR)	320,7788	3,53E-05
x10:x39	Living room Right Fin size x Inverse of North Axis/ Orientation in the terrain	-381,671	0,000392
x11:x14	Bedroom_1 Overhang size x Roof's Solar Absorptance	-235,881	3,11E-06
x11:x15	Bedroom_1 Overhang size x North Axis/ Orientation in the terrain	1,047235	4,47E-16
x11:x19	Bedroom_1 Overhang size x External Walls' U-value	-42,7339	0,006204
x11:x22	Bedroom_1 Overhang size x External Walls' Heat	0,313453	0,004487

	Capacity		
x11:x23	Bedroom_1 Overhang size x Internal Walls' Heat Capacity	0,267591	0,014708
x11:x40	Bedroom_1 Overhang size x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	-38,0826	6,54E-05
x11:x48	Bedroom_1 Overhang size x Inverse of Roof's Heat Capacity	-6283,54	3,09E-05
x12:x14	Bedroom_2 Overhang size x Roof's Solar Absorptance	-180,868	0,000329
x12:x17	Bedroom_2 Overhang size x Bedroom_2 Window to Wall Ratio (WWR)	451,1494	6,97E-09
x13:x14	Living room Overhang size x Roof's Solar Absorptance	-173,407	0,00064
x13:x15	Living room Overhang size x North Axis/ Orientation in the terrain	-0,25133	0,049674
x13:x17	Living room Overhang size x Bedroom_2 Window to Wall Ratio (WWR)	-214,925	0,007735
x13:x18	Living room Overhang size x Living room Window to Wall Ratio (WWR)	475,6046	1,41E-09
x13:x19	Living room Overhang size x External Walls' U-value	-58,3345	0,000248
x13:x21	Living room Overhang size x Roof's U-Value	-71,392	0,025666
x14:x15	Roof's Solar Absorptance x North Axis/ Orientation in the terrain	0,159975	0,023603
x14:x17	Roof's Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	367,3323	2,54E-16
x14:x18	Roof's Solar Absorptance x Living room Window to Wall Ratio (WWR)	494,6006	2,02E-29
x14:x19	Roof's Solar Absorptance x External Walls' U-value	181,8692	8,52E-98
x14:x21	Roof's Solar Absorptance x Roof's U-Value	-2122,23	0
x14:x24	Roof's Solar Absorptance x Roof's Heat Capacity	-0,54307	2,33E-18
x14:x39	Roof's Solar Absorptance x Inverse of North Axis/ Orientation in the terrain	-487,504	6,61E-14
x14:x40	Roof's Solar Absorptance x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	-57,3359	2,1E-27
x14:x48	Roof's Solar Absorptance x Inverse of Roof's Heat Capacity	5720,702	2,78E-06
x15:x19	North Axis/ Orientation in the terrain x External Walls' U-value	0,040484	0,070059
x15:x22	North Axis/ Orientation in the terrain x External Walls' Heat Capacity	0,000447	0,004094
x15:x40	North Axis/ Orientation in the terrain x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	0,206795	2,89E-52
x15:x48	North Axis/ Orientation in the terrain x Inverse of Roof's Heat Capacity	7,525179	0,001461

x17:x18	Bedroom_2 Window to Wall Ratio (WWR) x Living room Window to Wall Ratio (WWR)	318,7175	3,8E-06
x17:x19	Bedroom_2 Window to Wall Ratio (WWR) x External Walls' U-value	-100,539	3,58E-13
x17:x23	Bedroom_2 Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	-0,19837	0,039359
x17:x24	Bedroom_2 Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,3074	1,64E-05
x17:x40	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	-43,2287	8,14E-08
x17:x46	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	6268,585	0,011145
x18:x19	Living room Window to Wall Ratio (WWR) x External Walls' U-value	-82,8442	1,7E-10
x18:x24	Living room Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,31335	7,96E-06
x18:x40	Living room Window to Wall Ratio (WWR) x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	-47,2867	3,09E-09
x19:x21	External Walls' U-value x Roof's U-Value	-144,395	5,1E-173
x19:x22	External Walls' U-value x External Walls' Heat Capacity	-0,34184	2,77E-24
x19:x23	External Walls' U-value x Internal Walls' Heat Capacity	-0,23263	1,53E-33
x19:x24	External Walls' U-value x Roof's Heat Capacity	-0,22311	5,6E-35
x19:x39	External Walls' U-value x Inverse of North Axis/ Orientation in the terrain	-523,632	1E-29
x19:x40	External Walls' U-value x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	10,48896	5,24E-12
x19:x46	External Walls' U-value x Inverse of External Walls' Heat Capacity	4767,008	3,6E-08
x19:x48	External Walls' U-value x Inverse of Roof's Heat Capacity	1568,278	5,21E-06
x21:x23	Roof's U-Value x Internal Walls' Heat Capacity	-0,14394	0,000114
x21:x24	Roof's U-Value x Roof's Heat Capacity	-0,74904	2,64E-84
x21:x39	Roof's U-Value x Inverse of North Axis/ Orientation in the terrain	-248,817	6,23E-09
x21:x46	Roof's U-Value x Inverse of External Walls' Heat Capacity	8974,969	2,08E-21
x21:x48	Roof's U-Value x Inverse of Roof's Heat Capacity	4216,483	1,42E-08
x22:x24	External Walls' Heat Capacity x Roof's Heat Capacity	0,001281	6,19E-13
x22:x39	External Walls' Heat Capacity x Inverse of North Axis/ Orientation in the terrain	2,768684	3,9E-30

x23:x24	Internal Walls' Heat Capacity x Roof's Heat Capacity	0,001017	3,62E-14
x23:x39	Internal Walls' Heat Capacity x Inverse of North Axis/ Orientation in the terrain	1,681017	7,49E-19
x23:x40	Internal Walls' Heat Capacity x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	0,03713	0,001131
x23:x46	Internal Walls' Heat Capacity x Inverse of External Walls' Heat Capacity	-46,8797	1,89E-41
x23:x48	Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	-15,1352	4,83E-09
x24:x40	Roof's Heat Capacity x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	0,030903	0,000226
x24:x46	Roof's Heat Capacity x Inverse of External Walls' Heat Capacity	-17,9343	0,000497
x35:x39	Inverse of Bedroom_1 Overhang size x Inverse of North Axis/ Orientation in the terrain	-17,656	5,95E-09
x39:x40	Inverse of North Axis/ Orientation in the terrain x Inverse of Bedroom_1 Window to Wall Ratio (WWR)	77,0011	2,38E-10
x39:x46	Inverse of North Axis/ Orientation in the terrain x Inverse of External Walls' Heat Capacity	52481	1,2E-26
x39:x48	Inverse of North Axis/ Orientation in the terrain x Inverse of Roof's Heat Capacity	-5069,76	0,072726
x40:x46	Inverse of Bedroom_1 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	-939,124	0,000996
x46:x48	Inverse of External Walls' Heat Capacity x Inverse of Roof's Heat Capacity	931757,5	6,74E-45
x4^2	External Walls' Solar Absorptance^2	559,2501	3,69E-70
x10^2	Living room Right Fin size^2	-243,027	0,017286
x14^2	Roof's Solar Absorptance^2	982,538	2,2E-207
x15^2	North Axis/ Orientation in the terrain^2	0,017765	0
x19^2	External Walls' U-value^2	-55,8444	3,5E-210
x22^2	External Walls' Heat Capacity^2	0,002656	4,24E-22
x23^2	Internal Walls' Heat Capacity^2	0,000897	2,44E-09
x24^2	Roof's Heat Capacity^2	0,001593	1,17E-24
x39^2	Inverse of North Axis/ Orientation in the terrain^2	32,56589	1,82E-41
x40^2	Inverse of Bedroom_1 Window to Wall Ratio (WWR)^2	-2,8693	7,98E-06
x48^2	Inverse of Roof's Heat Capacity^2	-218561	2,01E-17

APPENDIX 05 - São Paulo/SP: Meta-model coefficients – Degree-hours of discomfort by heat (standard approach with regression floor)

Coefficient	Meaning	value	p-value
INTERCEPT	INTERCEPT	209,0965	3,57E-54
x4	External Walls' Solar Absorptance	-142,318	3,32E-33
x11	Bedroom_1 Overhang size	11,57586	0,248043
x13	Living room Overhang size	35,13246	0,001299
x14	Roof's Solar Absorptance	-313,121	2,2E-121
x16	Bedroom_1 Window to Wall Ratio (WWR)	-58,3168	0,000395
x17	Bedroom_2 Window to Wall Ratio (WWR)	-47,5932	3,94E-07
x18	Living room Window to Wall Ratio (WWR)	-42,1278	0,000443
x19	External Walls' U-value	-47,3152	5,9E-32
x21	Roof's U-Value	-170,638	2,9E-66
x23	Internal Walls' Heat Capacity	0,187527	1,31E-11
x27	Inverse of Living room Effective window ventilation area	17,42579	6,2E-05
x33	Inverse of Bedroom_2 Right Fin size	0,670124	0,010185
x46	Inverse of External Walls' Heat Capacity	-10970	6,84E-59
x48	Inverse of Roof's Heat Capacity	-5654,8	2,48E-36
x4:x11	External Walls' Solar Absorptance x Bedroom_1 Overhang size	-25,7689	0,025528
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	54,79794	1,08E-17
x4:x18	External Walls' Solar Absorptance x Living room Window to Wall Ratio (WWR)	21,50221	0,027303
x4:x19	External Walls' Solar Absorptance x External Walls' U-value	55,77705	4,5E-162
x4:x21	External Walls' Solar Absorptance x Roof's U-Value	32,08197	3,64E-16
x4:x23	External Walls' Solar Absorptance x Internal Walls' Heat Capacity	-0,05415	0,000118
x4:x46	External Walls' Solar Absorptance x Inverse of External Walls' Heat Capacity	4866,426	2,07E-41
x4:x48	External Walls' Solar Absorptance x Inverse of Roof's Heat Capacity	1934,396	2,15E-21
x11:x19	Bedroom_1 Overhang size x External Walls' U-value	-14,1075	7,87E-05
x11:x23	Bedroom_1 Overhang size x Internal Walls' Heat Capacity	0,066866	0,007631
x11:x48	Bedroom_1 Overhang size x Inverse of Roof's Heat Capacity	-1623,67	2,8E-06
x13:x14	Living room Overhang size x Roof's Solar Absorptance	-23,8267	0,040175

x13:x16	Living room Overhang size x Bedroom_1 Window to Wall Ratio (WWR)	-36,9951	0,040171
x13:x19	Living room Overhang size x External Walls' U-value	-13,5123	0,000182
x14:x16	Roof's Solar Absorptance x Bedroom_1 Window to Wall Ratio (WWR)	44,22432	6,39E-06
x14:x17	Roof's Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	46,05074	6,85E-06
x14:x18	Roof's Solar Absorptance x Living room Window to Wall Ratio (WWR)	28,3489	0,004541
x14:x19	Roof's Solar Absorptance x External Walls' U-value	18,92962	2,65E-22
x14:x21	Roof's Solar Absorptance x Roof's U-Value	146,2219	1,9E-267
x14:x23	Roof's Solar Absorptance x Internal Walls' Heat Capacity	-0,12287	2,71E-18
x14:x33	Roof's Solar Absorptance x Inverse of Bedroom_2 Right Fin size	0,466267	0,001684
x14:x46	Roof's Solar Absorptance x Inverse of External Walls' Heat Capacity	6190,598	2,51E-66
x14:x48	Roof's Solar Absorptance x Inverse of Roof's Heat Capacity	6090,088	1,8E-173
x16:x21	Bedroom_1 Window to Wall Ratio (WWR) x Roof's U-Value	30,3961	2,57E-07
x16:x23	Bedroom_1 Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	-0,074	0,00058
x16:x46	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	2535,154	2,46E-06
x16:x48	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	1360,055	1,3E-05
x17:x21	Bedroom_2 Window to Wall Ratio (WWR) x Roof's U-Value	20,89712	0,000575
x17:x33	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Bedroom_2 Right Fin size	-0,5553	0,012045
x17:x46	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	2039,182	0,000288
x17:x48	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	1533,531	1,4E-06
x18:x21	Living room Window to Wall Ratio (WWR) x Roof's U-Value	26,28055	1,72E-05
x18:x23	Living room Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	-0,057	0,008634
x18:x46	Living room Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	2040,648	0,00023
x18:x48	Living room Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	1879,125	1,54E-09
x19:x21	External Walls' U-value x Roof's U-Value	4,114495	0,00029

x19:x23	External Walls' U-value x Internal Walls' Heat Capacity	-0,03756	1,15E-17
x19:x27	External Walls' U-value x Inverse of Living room Effective window ventilation area	-4,72156	0,009332
x19:x33	External Walls' U-value x Inverse of Bedroom_2 Right Fin size	0,206007	3,08E-06
x19:x46	External Walls' U-value x Inverse of External Walls' Heat Capacity	2940,155	1,1E-158
x19:x48	External Walls' U-value x Inverse of Roof's Heat Capacity	767,2884	4,3E-37
x21:x23	Roof's U-Value x Internal Walls' Heat Capacity	-0,04472	1,66E-07
x21:x27	Roof's U-Value x Inverse of Living room Effective window ventilation area	-8,44865	0,021323
x21:x33	Roof's U-Value x Inverse of Bedroom_2 Right Fin size	-0,17966	0,046587
x21:x46	Roof's U-Value x Inverse of External Walls' Heat Capacity	3366,082	4,61E-54
x21:x48	Roof's U-Value x Inverse of Roof's Heat Capacity	3748,863	8,3E-180
x23:x33	Internal Walls' Heat Capacity x Inverse of Bedroom_2 Right Fin size	-0,0008	0,011919
x23:x46	Internal Walls' Heat Capacity x Inverse of External Walls' Heat Capacity	-7,31071	1,85E-20
x23:x48	Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	-4,61654	8,5E-26
x27:x33	Inverse of Living room Effective window ventilation area x Inverse of Bedroom_2 Right Fin size	-0,49387	0,000127
x27:x48	Inverse of Living room Effective window ventilation area x Inverse of Roof's Heat Capacity	-735,039	4,12E-05
x33:x48	Inverse of Bedroom_2 Right Fin size x Inverse of Roof's Heat Capacity	14,26025	0,005877
x46:x48	Inverse of External Walls' Heat Capacity x Inverse of Roof's Heat Capacity	293633,9	1,7E-145
x4^2	External Walls' Solar Absorptance^2	28,60354	6,04E-05
x14^2	Roof's Solar Absorptance^2	78,87161	4,51E-29
x16^2	Bedroom_1 Window to Wall Ratio (WWR)^2	26,923	0,036682
x19^2	External Walls' U-value^2	4,881887	9,24E-35
x21^2	Roof's U-Value^2	22,18825	8,19E-22
x23^2	Internal Walls' Heat Capacity^2	0,000133	0,000115
x33^2	Inverse of Bedroom_2 Right Fin size^2	0,003711	0,008683
x46^2	Inverse of External Walls' Heat Capacity^2	-56791,2	0,000216
x48^2	Inverse of Roof's Heat Capacity^2	-52405,2	1,57E-66

APPENDIX 06 - São Paulo/SP: Meta-model coefficients – Degree-hours of discomfort by heat (Non-zero approach with regression floor)

Coefficient	**Meaning**	**value**	**p-value**
INTERCEPT	INTERCEPT	378,9731	9,43E-15
x4	External Walls' Solar Absorptance	-205,863	6,73E-17
x5	Bedroom_1 Left Fin size	-11,5254	0,003621
x11	Bedroom_1 Overhang size	58,04928	3,77E-05
x12	Bedroom_2 Overhang size	-32,1959	0,004398
x13	Living room Overhang size	9,071032	0,366586
x14	Roof's Solar Absorptance	-671,798	6,08E-48
x16	Bedroom_1 Window to Wall Ratio (WWR)	24,80705	0,172697
x17	Bedroom_2 Window to Wall Ratio (WWR)	-23,8698	0,234426
x18	Living room Window to Wall Ratio (WWR)	-55,8355	0,012285
x19	External Walls' U-value	-55,0305	7,43E-25
x21	Roof's U-Value	-362,528	3,83E-30
x22	External Walls' Heat Capacity	0,275397	0,000188
x23	Internal Walls' Heat Capacity	0,304049	1,16E-08
x24	Roof's Heat Capacity	0,69502	5,8E-20
x33	Inverse of Bedroom_2 Right Fin size	-0,04448	0,866359
x41	Inverse of Bedroom_2 Window to Wall Ratio (WWR)	5,104988	0,000508
x45	Inverse of Roof's U-Value	-85,2232	5,93E-09
x46	Inverse of External Walls' Heat Capacity	-8705,61	9,45E-12
x48	Inverse of Roof's Heat Capacity	-4156,2	1,24E-07
x4:x11	External Walls' Solar Absorptance x Bedroom_1 Overhang size	-55,7242	0,000497
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	194,791	2,41E-55
x4:x18	External Walls' Solar Absorptance x Living room Window to Wall Ratio (WWR)	43,68695	0,001157
x4:x19	External Walls' Solar Absorptance x External Walls' U-value	102,2987	4,9E-294
x4:x21	External Walls' Solar Absorptance x Roof's U-Value	94,48206	1,62E-63
x4:x22	External Walls' Solar Absorptance x External Walls' Heat Capacity	-0,34993	3,29E-20
x4:x23	External Walls' Solar Absorptance x Internal Walls' Heat Capacity	-0,17166	2,01E-16
x4:x24	External Walls' Solar Absorptance x Roof's Heat Capacity	-0,30419	4,44E-39
x4:x41	External Walls' Solar Absorptance x Inverse of	-4,87267	0,007654

	Bedroom_2 Window to Wall Ratio (WWR)		
x4:x46	External Walls' Solar Absorptance x Inverse of External Walls' Heat Capacity	4625,35	7,72E-09
x4:x48	External Walls' Solar Absorptance x Inverse of Roof's Heat Capacity	1471,436	1,81E-06
x11:x19	Bedroom_1 Overhang size x External Walls' U-value	-18,6852	7E-07
x11:x46	Bedroom_1 Overhang size x Inverse of External Walls' Heat Capacity	-1926,78	0,011736
x11:x48	Bedroom_1 Overhang size x Inverse of Roof's Heat Capacity	-1447,7	0,000145
x12:x18	Bedroom_2 Overhang size x Living room Window to Wall Ratio (WWR)	46,07613	0,04825
x13:x19	Living room Overhang size x External Walls' U-value	-9,30435	0,014397
x13:x33	Living room Overhang size x Inverse of Bedroom_2 Right Fin size	1,061089	0,012862
x13:x46	Living room Overhang size x Inverse of External Walls' Heat Capacity	-2430,05	0,001618
x13:x48	Living room Overhang size x Inverse of Roof's Heat Capacity	-826,618	0,034632
x14:x16	Roof's Solar Absorptance x Bedroom_1 Window to Wall Ratio (WWR)	60,48912	8,27E-05
x14:x17	Roof's Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	59,37387	0,000205
x14:x18	Roof's Solar Absorptance x Living room Window to Wall Ratio (WWR)	45,38299	0,003385
x14:x19	Roof's Solar Absorptance x External Walls' U-value	41,25817	7,63E-47
x14:x21	Roof's Solar Absorptance x Roof's U-Value	402,8104	1,7E-132
x14:x22	Roof's Solar Absorptance x External Walls' Heat Capacity	-0,4033	9,72E-19
x14:x23	Roof's Solar Absorptance x Internal Walls' Heat Capacity	-0,24136	7,18E-24
x14:x24	Roof's Solar Absorptance x Roof's Heat Capacity	-0,4663	5,65E-73
x14:x33	Roof's Solar Absorptance x Inverse of Bedroom_2 Right Fin size	0,980809	0,000141
x14:x45	Roof's Solar Absorptance x Inverse of Roof's U-Value	118,8332	3,47E-14
x14:x46	Roof's Solar Absorptance x Inverse of External Walls' Heat Capacity	6141,33	3,98E-12
x14:x48	Roof's Solar Absorptance x Inverse of Roof's Heat Capacity	5420,793	4,18E-50
x16:x21	Bedroom_1 Window to Wall Ratio (WWR) x Roof's U-Value	28,51599	8,56E-05
x16:x22	Bedroom_1 Window to Wall Ratio (WWR) x External Walls' Heat Capacity	-0,11861	8,43E-05

x16:x23	Bedroom_1 Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	-0,1004	0,000673
x16:x24	Bedroom_1 Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,09137	0,002248
x16:x48	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	2599,851	1,13E-08
x17:x21	Bedroom_2 Window to Wall Ratio (WWR) x Roof's U-Value	33,57022	1,16E-05
x17:x23	Bedroom_2 Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	-0,09893	0,000829
x17:x24	Bedroom_2 Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,06203	0,043406
x17:x46	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	4256,2	1,23E-09
x17:x48	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	2649,202	4,41E-09
x18:x21	Living room Window to Wall Ratio (WWR) x Roof's U-Value	43,14944	6,09E-09
x18:x23	Living room Window to Wall Ratio (WWR) x Internal Walls' Heat Capacity	-0,10453	0,000308
x18:x24	Living room Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,12446	3,97E-05
x18:x46	Living room Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	3660,921	5,07E-08
x18:x48	Living room Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	1654,549	0,000214
x19:x21	External Walls' U-value x Roof's U-Value	22,09194	3,51E-60
x19:x22	External Walls' U-value x External Walls' Heat Capacity	-0,1062	3,88E-30
x19:x23	External Walls' U-value x Internal Walls' Heat Capacity	-0,07222	6,1E-44
x19:x24	External Walls' U-value x Roof's Heat Capacity	-0,09551	1,12E-74
x19:x33	External Walls' U-value x Inverse of Bedroom_2 Right Fin size	0,218991	2,26E-05
x19:x46	External Walls' U-value x Inverse of External Walls' Heat Capacity	2175,135	2,64E-25
x19:x48	External Walls' U-value x Inverse of Roof's Heat Capacity	258,3311	0,000736
x21:x22	Roof's U-Value x External Walls' Heat Capacity	-0,23472	1,9E-30
x21:x23	Roof's U-Value x Internal Walls' Heat Capacity	-0,12132	3,93E-27
x21:x24	Roof's U-Value x Roof's Heat Capacity	-0,40882	1,47E-66
x21:x46	Roof's U-Value x Inverse of External Walls' Heat Capacity	1864,055	7,52E-06

x21:x48	Roof's U-Value x Inverse of Roof's Heat Capacity	2268,019	3,55E-37
x22:x23	External Walls' Heat Capacity x Internal Walls' Heat Capacity	0,000335	1,18E-05
x22:x24	External Walls' Heat Capacity x Roof's Heat Capacity	0,000551	1,75E-10
x22:x33	External Walls' Heat Capacity x Inverse of Bedroom_2 Right Fin size	-0,00146	0,008529
x22:x48	External Walls' Heat Capacity x Inverse of Roof's Heat Capacity	-6,16094	2,99E-07
x23:x24	Internal Walls' Heat Capacity x Roof's Heat Capacity	0,000398	1,84E-18
x23:x33	Internal Walls' Heat Capacity x Inverse of Bedroom_2 Right Fin size	-0,0021	2,98E-05
x23:x46	Internal Walls' Heat Capacity x Inverse of External Walls' Heat Capacity	-5,87328	0,000391
x23:x48	Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	-5,30587	7,77E-16
x24:x33	Roof's Heat Capacity x Inverse of Bedroom_2 Right Fin size	-0,00088	0,017034
x24:x45	Roof's Heat Capacity x Inverse of Roof's U-Value	-0,08679	0,000156
x24:x46	Roof's Heat Capacity x Inverse of External Walls' Heat Capacity	-11,2287	4,22E-10
x46:x48	Inverse of External Walls' Heat Capacity x Inverse of Roof's Heat Capacity	126041,4	3,8E-06
x4^2	External Walls' Solar Absorptance^2	64,23986	5,1E-10
x14^2	Roof's Solar Absorptance^2	124,8602	6,76E-24
x19^2	External Walls' U-value^2	6,95283	2,36E-47
x21^2	Roof's U-Value^2	65,10893	1,5E-16
x22^2	External Walls' Heat Capacity^2	0,000747	8,15E-17
x23^2	Internal Walls' Heat Capacity^2	0,00032	6,93E-12
x24^2	Roof's Heat Capacity^2	0,000632	7,72E-36
x48^2	Inverse of Roof's Heat Capacity^2	-42880,6	3,58E-12

APPENDIX 07 - Manaus/AM: Meta-model coefficients – Degree-hours of discomfort by heat (standard approach with regression floor)

Coefficient	Meaning	value	p-value
INTERCEPT	INTERCEPT	911,8894	4,62E-13
x4	External Walls' Solar Absorptance	-1850,12	2,44E-82
x5	Bedroom_1 Left Fin size	308,6149	0,004451
x6	Bedroom_2 Left Fin size	48,42138	0,475329
x8	Bedroom_1 Right Fin size	468,2416	0,000621
x9	Bedroom_2 Right Fin size	390,6307	4,08E-05
x11	Bedroom_1 Overhang size	393,9732	1,18E-05
x12	Bedroom_2 Overhang size	155,6619	0,164865
x13	Living room Overhang size	580,1741	6,48E-12
x14	Roof's Solar Absorptance	-3010,46	2,1E-199
x15	North Axis/ Orientation in the terrain	-0,27827	0,012303
x16	Bedroom_1 Window to Wall Ratio (WWR)	-296,258	0,019323
x17	Bedroom_2 Window to Wall Ratio (WWR)	-539,48	1,65E-05
x18	Living room Window to Wall Ratio (WWR)	-666,16	2,38E-07
x19	External Walls' U-value	-216,528	3,45E-23
x21	Roof's U-Value	-1243,23	3,8E-118
x24	Roof's Heat Capacity	1,68734	2,87E-15
x25	Inverse of Bedroom_1 Effective window ventilation area	67,28971	0,0075
x31	Inverse of Living room Left Fin size	-5,02796	9,85E-06
x32	Inverse of Bedroom_1 Right Fin size	-0,52004	0,510173
x34	Inverse of Living room Right Fin size	0,52491	0,498399
x43	Inverse of External Walls' U-value	235,9633	6,54E-15
x46	Inverse of External Walls' Heat Capacity	-28572,8	2,28E-07
x47	Inverse of Internal Walls' Heat Capacity	-20062,9	1,21E-05
x48	Inverse of Roof's Heat Capacity	-39261,2	4,97E-23
x4:x6	External Walls' Solar Absorptance x Bedroom_2 Left Fin size	-161,352	0,016394
x4:x11	External Walls' Solar Absorptance x Bedroom_1 Overhang size	-155,998	0,019908
x4:x12	External Walls' Solar Absorptance x Bedroom_2 Overhang size	-197,806	0,002829
x4:x13	External Walls' Solar Absorptance x Living room Overhang size	-183,121	0,005272
x4:x14	External Walls' Solar Absorptance x Roof's Solar Absorptance	792,1097	1,1E-101

x4:x16	External Walls' Solar Absorptance x Bedroom_1 Window to Wall Ratio (WWR)	270,5399	2,58E-06
x4:x17	External Walls' Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	226,356	7,85E-05
x4:x18	External Walls' Solar Absorptance x Living room Window to Wall Ratio (WWR)	284,6164	7,47E-07
x4:x19	External Walls' Solar Absorptance x External Walls' U-value	907,7453	0
x4:x21	External Walls' Solar Absorptance x Roof's U-Value	253,1698	7,86E-30
x4:x24	External Walls' Solar Absorptance x Roof's Heat Capacity	-0,53998	1,1E-11
x4:x32	External Walls' Solar Absorptance x Inverse of Bedroom_1 Right Fin size	1,868761	0,020749
x4:x43	External Walls' Solar Absorptance x Inverse of External Walls' U-value	110,1346	8,89E-11
x4:x46	External Walls' Solar Absorptance x Inverse of External Walls' Heat Capacity	51882,5	2,2E-124
x4:x47	External Walls' Solar Absorptance x Inverse of Internal Walls' Heat Capacity	12085,61	7,03E-09
x4:x48	External Walls' Solar Absorptance x Inverse of Roof's Heat Capacity	6593,142	2,66E-05
x5:x12	Bedroom_1 Left Fin size x Bedroom_2 Overhang size	243,9179	0,046649
x5:x14	Bedroom_1 Left Fin size x Roof's Solar Absorptance	-140,524	0,035856
x5:x18	Bedroom_1 Left Fin size x Living room Window to Wall Ratio (WWR)	-206,912	0,04961
x5:x19	Bedroom_1 Left Fin size x External Walls' U-value	-92,8213	0,005869
x5:x32	Bedroom_1 Left Fin size x Inverse of Bedroom_1 Right Fin size	-3,09938	0,039812
x5:x43	Bedroom_1 Left Fin size x Inverse of External Walls' U-value	-66,3944	0,035854
x5:x46	Bedroom_1 Left Fin size x Inverse of External Walls' Heat Capacity	-10676	0,007401
x6:x17	Bedroom_2 Left Fin size x Bedroom_2 Window to Wall Ratio (WWR)	-217,089	0,038712
x6:x24	Bedroom_2 Left Fin size x Roof's Heat Capacity	0,303552	0,004626
x8:x19	Bedroom_1 Right Fin size x External Walls' U-value	-169,982	2,95E-07
x8:x43	Bedroom_1 Right Fin size x Inverse of External Walls' U-value	-86,3336	0,005826
x8:x46	Bedroom_1 Right Fin size x Inverse of External Walls' Heat Capacity	11726,31	0,018486
x8:x48	Bedroom_1 Right Fin size x Inverse of Roof's Heat Capacity	-4275,67	0,035669
x9:x14	Bedroom_2 Right Fin size x Roof's Solar Absorptance	-133,26	0,044852

x9:x17	Bedroom_2 Right Fin size x Bedroom_2 Window to Wall Ratio (WWR)	-270,203	0,009488
x9:x47	Bedroom_2 Right Fin size x Inverse of Internal Walls' Heat Capacity	-11684,8	0,001533
x11:x14	Bedroom_1 Overhang size x Roof's Solar Absorptance	-300,391	6,87E-06
x11:x16	Bedroom_1 Overhang size x Bedroom_1 Window to Wall Ratio (WWR)	-283,935	0,007
x11:x21	Bedroom_1 Overhang size x Roof's U-Value	-137,172	0,000702
x11:x24	Bedroom_1 Overhang size x Roof's Heat Capacity	0,267408	0,01369
x11:x34	Bedroom_1 Overhang size x Inverse of Living room Right Fin size	-3,91906	0,008649
x11:x46	Bedroom_1 Overhang size x Inverse of External Walls' Heat Capacity	-9792,22	0,012519
x12:x14	Bedroom_2 Overhang size x Roof's Solar Absorptance	-272,818	5,04E-05
x12:x17	Bedroom_2 Overhang size x Bedroom_2 Window to Wall Ratio (WWR)	-565,38	6,28E-08
x12:x24	Bedroom_2 Overhang size x Roof's Heat Capacity	0,297132	0,005684
x12:x46	Bedroom_2 Overhang size x Inverse of External Walls' Heat Capacity	-8479,82	0,030252
x12:x47	Bedroom_2 Overhang size x Inverse of Internal Walls' Heat Capacity	-8393,31	0,028185
x13:x14	Living room Overhang size x Roof's Solar Absorptance	-209,114	0,001508
x13:x18	Living room Overhang size x Living room Window to Wall Ratio (WWR)	-421,627	5,6E-05
x13:x21	Living room Overhang size x Roof's U-Value	-140,294	0,000354
x13:x34	Living room Overhang size x Inverse of Living room Right Fin size	-3,42052	0,016614
x13:x47	Living room Overhang size x Inverse of Internal Walls' Heat Capacity	-13082,2	0,000561
x13:x48	Living room Overhang size x Inverse of Roof's Heat Capacity	-12577,4	8,91E-10
x14:x15	Roof's Solar Absorptance x North Axis/ Orientation in the terrain	0,300336	0,001014
x14:x16	Roof's Solar Absorptance x Bedroom_1 Window to Wall Ratio (WWR)	606,2887	3,69E-26
x14:x17	Roof's Solar Absorptance x Bedroom_2 Window to Wall Ratio (WWR)	547,5171	1,32E-21
x14:x18	Roof's Solar Absorptance x Living room Window to Wall Ratio (WWR)	497,4884	4,53E-18
x14:x19	Roof's Solar Absorptance x External Walls' U-value	101,4124	8,63E-09

x14:x21	Roof's Solar Absorptance x Roof's U-Value	1926,697	0
x14:x24	Roof's Solar Absorptance x Roof's Heat Capacity	-1,70997	5,2E-97
x14:x43	Roof's Solar Absorptance x Inverse of External Walls' U-value	-70,9483	2,83E-05
x14:x46	Roof's Solar Absorptance x Inverse of External Walls' Heat Capacity	48938,73	4,7E-112
x14:x47	Roof's Solar Absorptance x Inverse of Internal Walls' Heat Capacity	19379,41	4,61E-20
x14:x48	Roof's Solar Absorptance x Inverse of Roof's Heat Capacity	36554,19	1,2E-121
x15:x18	North Axis/ Orientation in the terrain x Living room Window to Wall Ratio (WWR)	0,316551	0,026577
x15:x21	North Axis/ Orientation in the terrain x Roof's U-Value	0,106798	0,051286
x15:x24	North Axis/ Orientation in the terrain x Roof's Heat Capacity	-0,00034	0,019017
x15:x46	North Axis/ Orientation in the terrain x Inverse of External Walls' Heat Capacity	10,23942	0,051698
x16:x17	Bedroom_1 Window to Wall Ratio (WWR) x Bedroom_2 Window to Wall Ratio (WWR)	245,7963	0,005512
x16:x18	Bedroom_1 Window to Wall Ratio (WWR) x Living room Window to Wall Ratio (WWR)	266,7729	0,002918
x16:x21	Bedroom_1 Window to Wall Ratio (WWR) x Roof's U-Value	90,80791	0,008612
x16:x24	Bedroom_1 Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,38619	0,001751
x16:x25	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of Bedroom_1 Effective window ventilation area	-143,52	0,006686
x16:x46	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	14812,75	2,11E-05
x16:x47	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of Internal Walls' Heat Capacity	8711,905	0,005764
x16:x48	Bedroom_1 Window to Wall Ratio (WWR) x Inverse of Roof's Heat Capacity	14835,55	5,84E-11
x17:x18	Bedroom_2 Window to Wall Ratio (WWR) x Living room Window to Wall Ratio (WWR)	307,7179	0,000633
x17:x21	Bedroom_2 Window to Wall Ratio (WWR) x Roof's U-Value	188,6714	4,79E-08
x17:x24	Bedroom_2 Window to Wall Ratio (WWR) x Roof's Heat Capacity	-0,45313	0,000317
x17:x46	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of External Walls' Heat Capacity	14969,28	3,81E-06
x17:x47	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of Internal Walls' Heat Capacity	13441,73	5,19E-05
x17:x48	Bedroom_2 Window to Wall Ratio (WWR) x Inverse of	16297,15	2,47E-11

	Roof’s Heat Capacity		
x18:x21	Living room Window to Wall Ratio (WWR) x Roof’s U-Value	81,86552	0,01702
x18:x24	Living room Window to Wall Ratio (WWR) x Roof’s Heat Capacity	-0,36643	0,003386
x18:x34	Living room Window to Wall Ratio (WWR) x Inverse of Living room Right Fin size	3,231787	0,012141
x18:x46	Living room Window to Wall Ratio (WWR) x Inverse of External Walls’ Heat Capacity	18605,07	4,26E-08
x18:x47	Living room Window to Wall Ratio (WWR) x Inverse of Internal Walls’ Heat Capacity	12246,53	0,000138
x18:x48	Living room Window to Wall Ratio (WWR) x Inverse of Roof’s Heat Capacity	9196,268	0,000112
x19:x24	External Walls’ U-value x Roof’s Heat Capacity	-0,24571	2,47E-24
x19:x31	External Walls’ U-value x Inverse of Living room Left Fin size	2,500773	2,75E-08
x19:x46	External Walls’ U-value x Inverse of External Walls’ Heat Capacity	19191,14	2,69E-83
x19:x47	External Walls’ U-value x Inverse of Internal Walls’ Heat Capacity	5209,872	4,44E-18
x19:x48	External Walls’ U-value x Inverse of Roof’s Heat Capacity	1689,813	0,000436
x21:x24	Roof’s U-Value x Roof’s Heat Capacity	-1,16593	2,6E-126
x21:x31	Roof’s U-Value x Inverse of Living room Left Fin size	1,126068	0,026995
x21:x46	Roof’s U-Value x Inverse of External Walls’ Heat Capacity	16682,36	1,58E-38
x21:x47	Roof’s U-Value x Inverse of Internal Walls’ Heat Capacity	12566,95	1E-23
x21:x48	Roof’s U-Value x Inverse of Roof’s Heat Capacity	15021,79	1,7E-60
x24:x46	Roof’s Heat Capacity x Inverse of External Walls’ Heat Capacity	-62,1312	4,03E-41
x24:x47	Roof’s Heat Capacity x Inverse of Internal Walls’ Heat Capacity	-31,2748	2,96E-12
x25:x48	Inverse of Bedroom_1 Effective window ventilation area x Inverse of Roof’s Heat Capacity	2753,509	0,006277
x31:x43	Inverse of Living room Left Fin size x Inverse of External Walls’ U-value	1,076889	0,003813
x31:x48	Inverse of Living room Left Fin size x Inverse of Roof’s Heat Capacity	88,7408	0,000912
x32:x46	Inverse of Bedroom_1 Right Fin size x Inverse of External Walls’ Heat Capacity	256,1624	3,93E-05
x34:x48	Inverse of Living room Right Fin size x Inverse of Roof’s Heat Capacity	54,14534	0,033488
x43:x46	Inverse of External Walls’ U-value x Inverse of	-5646,37	1,44E-08

	External Walls' Heat Capacity		
x46:x47	Inverse of External Walls' Heat Capacity x Inverse of Internal Walls' Heat Capacity	1493300	4,85E-32
x46:x48	Inverse of External Walls' Heat Capacity x Inverse of Roof's Heat Capacity	1628899	1,89E-77
x47:x48	Inverse of Internal Walls' Heat Capacity x Inverse of Roof's Heat Capacity	741422,3	2,46E-20
x4^2	External Walls' Solar Absorptance^2	286,135	3,22E-12
x8^2	Bedroom_1 Right Fin size^2	-431,147	0,015436
x9^2	Bedroom_2 Right Fin size^2	-336,007	0,012734
x12^2	Bedroom_2 Overhang size^2	326,389	0,01687
x14^2	Roof's Solar Absorptance^2	1043,219	1,4E-136
x17^2	Bedroom_2 Window to Wall Ratio (WWR)^2	224,3875	0,003441
x18^2	Living room Window to Wall Ratio (WWR)^2	193,6553	0,011336
x21^2	Roof's U-Value^2	237,8337	3,07E-72
x24^2	Roof's Heat Capacity^2	0,002055	9,13E-24
x43^2	Inverse of External Walls' U-value^2	-33,5901	2,27E-09
x46^2	Inverse of External Walls' Heat Capacity^2	-1833500	5,88E-85
x47^2	Inverse of Internal Walls' Heat Capacity^2	-549903	2,53E-10
x48^2	Inverse of Roof's Heat Capacity^2	-428602	1,19E-34