Parametric procedures for environmental adequacy of architectural conception: Methodological proposal

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Procedimentos paramétricos para a adequação ambiental da concepção arquitetônica: Proposta metodológica

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Abstract

Computational tools have redefined the architectural design practice, with respects to the environmental performance of buildings, since the decade of 1990. However, the environmental assessment of the design of buildings with the use of computer simulations is a process and, for this reason, do not guarantee the development of building designs adequate to the local climate. For this purpose, the environmental architectural approach, considered here, is the one in which the environmental adequacy is the result of the maximization of passive strategies, characterizing the architectural practice known as *Bioclimatism* and configuring the so-called *Environmental Building*. The efficient application of design parameters in the environmental adequacy of architectural requires the understanding of the specificities of the climatic context and of the consequent role of each design parameter in the interactions between internal and external environments. The objective of this work is a methodological proposal of qualifications of the design process for the environmental adequacy of buildings during the architectural conceptual phase, by means of parametric analysis and computer simulations, encompassing aspects of thermal performance and daylight. Examples of the application of parts of this method demonstrate the informative role of analytical studies in the creative architectural process, offering a range of design solutions of adequate performance.

Resumo

Desde a década de 1990, as ferramentas computacionais vêm redefinindo a prática do projeto arquitetônico, com vistas ao desempenho ambiental das edificações. Contudo, a avaliação de desempenho ambiental de projetos de edifícios por meio do uso de simulações computacionais é um processo e, por isso, não garante a realização de projetos adequados ao clima local. Nesse contexto, a abordagem ambiental da arquitetura aqui contemplada é aquela em que a adequação ambiental é resultado da maximização das estratégias passivas, caracterizando a prática arquitetônica conhecida como *Bioclimatismo* e configurando o chamado *Edifício Ambiental*. A aplicação eficiente dos parâmetros de projeto na adequação ambiental da arquitetura passa pelo entendimento das especificidades do clima em questão e do consequente papel de cada parâmetro nas interações entre ambientes externo e interno. O objetivo desse trabalho é a apresentação de uma proposta metodológica de qualificação do processo projetual para a adequação ambiental de edifícios na etapa de concepção, por meio de análises paramétricas de simulação computacional, englobando aspectos do desempenho térmico e da iluminação natural. Exemplos de aplicação de partes do método demonstram o papel informativo de estudos analíticos no processo criativo da arquitetura, oferecendo um leque de soluções projetuais de desempenho adequado.

Introduction

The use of computational simulation for the assessment of environmental performance of the design of buildings, including the fields of thermal, lighting, and energy demand, is not a new practice, since the first simulation tools date to the 1960s and 1970s (MALKAWI; AUGENBROE, 2004). However, it was in the 1990s that the insertion of advanced computational methods marked the design refinement of a generation of architecture icons built in Europe and in the United States, with the exploration of daylight and natural ventilation (GONÇALVES; UMAKOSHI, 2010; GONÇALVES; BODE, 2011).

In the example of such icons, the exploration of the impact of the various architectonical aspects on the buildings' environmental performance, by means of advanced techniques of computational simulation, began. Thus, the efficiency of design strategies derived from principles of building physics and from the climate context became quantifiable and revised throughout the design phases. Nevertheless, it must be considered that such performance assessment is essentially a process. In this context, what will ensure the realization of projects adequate to local climate is, essentially, the environmental approach of the architectural concept.

Kowaltowski et al. (2006) state that design methodology is a procedure organized to lead the creation development to a given result, by means of rationalization of creative activities based on ever more complex problems. These methodologies are developed from abstractions and reductions that permit comprehending the phenomenon of the design process. Thus, when choosing the environmental parameters to be utilized in the development of the project, we chose the following path. To comprehend how utilizing these parameters in the generation of the form facilitates the technical understanding of the adopted procedures. Further yet, the aforementioned authors state that, to reach such understanding, the visualization of the physical phenomena is essential, through images adequate to the design exercise to stimulate the creative process.

Olgyay (1963) originally established the relationship between climate and Architecture, introducing the term Bioclimatic Approach, with the purpose of providing the user with comfortable spaces, resorting exclusively to architectonic resources, that is, promoting an architecture known for the use of passive strategies. Complementing, Romero (2015) explains that, in the concept of Bioclimatism, the architectonic project is conceived for natural environmental conditions in the buildings to be achieved, by means of an integrated approach of the thermal qualities, daylight, sound, and colors.

Following this line of reasoning, the concept of the best environmentally performing building herein contemplated and presented by Gonçalves and Bode (2015), who introduced the term Environmental Building, goes with the precepts of the Bioclimatic Approach and with the ideas proposed by Hawkes (2008), in which architectural and environmental qualities are presented as a sole aspect of the environment, fruit of the profound knowledge of the particularities of climate, daylight, and solar geometry.

Hence, the definition of the so-called Environmental Building (GONÇALVES; BODE, 2015) is contrary to the premise of dependence of air conditioning and artificial lighting building systems, widely spread throughout the world since the mid-twentieth century, as expounded in Banham (1984). On the contrary, the interaction between means and the principles of environmental diversity put by Steemers and Steane (2004) is incorporated.

Instead of isolating itself from the external climate, the Environmental Building benefits from the relationship with the exterior, by means of design strategies, in which environmental variables such as access to the sun and exploration of daylight, visual communication between interior and exterior, and natural ventilation have the potential of aggregating quality and authenticity to the architecture. To this end, Gonçalves and Duarte (2006) stress the role of the following aspects of the project: form, specification of building components, façade treatment, opening typology, internal space layout, among others. Notwithstanding, in reference to Hawkes (1996), the tendency of dealing with climatic variables, instead of isolating from them, is not a new approach, being present in examples of architecture from all times, places, and cultures.

In respect to the architectonical design, a series of studies and works on architectural projects conducted in the past decade have demonstrated that analytical studies on environmental performance play a central role in the creative process of project-design decisions (YANNAS, 2011; GONÇALVES; UMAKOSHI-KUNIOCHI; MOURA, 2015). Kolaveric and Malawaki (2005) note that the process of computational assessment of building environmental performance using advanced simulation tools offers a never-before-seen approximation between architectural conception and environmental conditions, associated with the project's characteristics.

The computational resources made agile the analysis of the architectural design parameters called Parametric Sensitivity Analysis by Pisello et al. (2012), characterized as an important supporting method to the design process and to the research focused on studies of thermal and lighting building performance, in recognition of the most effective strategies to a given problem, in the stage of architectural conception. Parallel to it, the benefits of analytical studies for building environmental and energy performance are more significant when done in the early phases of projects, while, when introduced only in late stages, the effects of such analyses are reduced to corrections of restricted reach for the environmental performance of buildings (ASHRAE, 2018).

In the ambit of the Environmental Building, the goal of this paper is the presentation of a qualification methodological proposal of the design process for the environmental adequacy of buildings in the stage of architectural conception, by means of computational simulation parametric analyses, encompassing aspects of thermal performance and daylight . This proposal rests on the methodology-based propositional works by Umakoshi (2010) and Gonçalves (2014) and is based on the understanding of the impacts of architectural design parameters on buildings' environmental performance, in a given climate context, and within the possibilities of computational analytical procedures, regarding the study of alternativ scenarios and multi-criteria analyses.

Analytical studies for the architectural conception: Methodological proposal and examples of applicability

This methodological proposal for the insertion of analytical procedures of environmental adequacy in the conception stage of the architectural design-project, with emphasis on thermal and daylighting issues, results from a critical revision of the general guidelines for the analysis of the environmental response of architectural conception studies initially established by Umakoshi (2010) and Gonçalves (2014).

Umakoshi (2010) suggests an initial systematization of design parameters to be contemplated for the elaboration of simplified analysis models of architectural environmental performance, including occupation, orientation, form, materials, solar protection, glazed area, and surrounding variables. In said work, the author stresses the importance of using simplified models for understanding the role of basic design parameters, associated to form and encasement composition, in a given climatic context.

Complementing, Gonçalves (2014) demonstrates, by means of case studies of conceptual architectural design exercises, the potential of parametric studies of environmental performance (thermal, energy, and daylighting) assessment, with computational simulations and simplified calculations, in which the impact of each design variable is verified in isolation. For instance: the impact of solar protections (in different orientations), thermal insulation, glazed areas (in different orientations), exposure area (façade area to floor area), and other parameters. The author also lists various forms of performance analyses result evaluation according to the preliminary architectural design approach for space climatizing, emphasizing the importance of beginning the analyses with the calculation of operational temperatures and illuminance values throughout typical day of the year, instead of, for example, cooling or heating thermal loads.

The proposal herein presented deepens the study of architectural conception, with a detailing of the set of parameters appearing in the methodological approaches by Umakoshi (2010) and Gonçalves (2014), which are related to specific passive strategies and goals of environmental adequacy, maintaining the idea of the construction of assessment base-cases. As in the aforementioned works, this proposal is based on the understanding of the impact of the architectural design parameters on the buildings' thermal and daylighting conditions, relying on the technical input of the possibilities of assessment procedures by means of computational simulations.

The methodological strategy is structured in three stages: (1) Climatic Analysis, in which the environmental adequacy goals and the ensuing project strategies are established, from the analysis of local climate; (2) Elaboration of the Base-Case, comprehending the identification of project parameters to be applied in the elaboration of base-cases and alternative scenarios; and (3) Parametric Analyses, configuring the parametric analysis of conceptual solutions, with the elaboration and analysis of cumulative and combinatory scenarios of alternative solutions, concluding with the formulation of guidelines for the architectural concept (Figure 1).

Nevertheless, it is worth pointing out that, despite the mention of computational simulation tools, their recommendation for the application in the performance assessment procedures is not part of this proposal. Thus, computational tools for the assessment of environmental performance are not presented here. In fact, the focus of this methodological proposal is on the elaboration of base-cases for spaces and the formulation of parametric and analytical studies of alternative scenarios for the testing of the environmental performance of architectural strategies, in the stage of design-concept. Such testing serves to increase the domain of the architectural possibilities and restrictions, linked to the local climate. Complementing, the development of a logic for the formulation of such base-cases precedes the use of calculation and simulation tools for their environmental performance.

Figure 1 - Flowchart of the general stages of the methodological proposal for the insertion of environmental adequacy analytical procedures in the stage of architectural conception. Source: The authors.

The same applies to the discussion on performance criteria. In this regard, indicators to be extracted from the technical studies (such as Operational Temperature, Dayight Factor, Useful Illuminances, and others) are suggested, but performance targets associated with such indicators are not referenced, since performance targets themselves will depend on local climate and other design variables, such as use and occupancy, which are not part of the scope of the here proposed methodology.

Climatic analysis

The analysis of the project's local climate, the *Climatic Analysis*, constitutes the first stage of this methodological proposal, with three subsequent steps: Step 1 – Analysis of Climatic Variants; Step 2 – Definition of the Environmental Adequacy Goals; and Step 3 – Identification of Project Strategies (Figure 2). Step 1 encompasses the reading of data on direct and diffuse radiation, wind speed and predominance, types of sky, and luminosity, always considering daily, weekly, and monthly oscillation. Thus, the limitations and potentialities of a given climate to architecture are clarified.

It is worth mentioning that the proposed climatic analysis does not exclude the role of prior knowledge of a climatic classification for the comprehension of the specific conditions of a given place's climate, with Köppen's (PEEL et al., 2007) classification being the most widely used presently, due to its high level of detailing.

The observation of the relationships between these variables is part of the climatic analysis, including: daily (for representative days of the year) and monthly (ratio between maximum and minimum temperatures) thermal amplitude (Δt), difference between maximum and minimum temperature and humidity over the months, relationship between air temperature and global radiation, and, lastly, relationship between direct and diffuse radiation over the months. The significance of each of these relationships for the environmental performance of architecture varies according to the climatic context, as explicit in Figure 2, which presents the various actions that constitute Step 1 of the Climatic Analysis.

Climate study is based on a database for the 8,760 hours of the year. There are many types of climate databases, one of which the Test Meteorological Year (TMY).[1] Beyond the analyses of a typical current year, the environmental adequacy of buildings brings the possibility of including the analysis of scenarios for future climate conditions, with the study of climate scenarios proposed by the Intergovernmental Panel on Climate Change – IPCC (2017). In addition, it is also possible to adjust the climate databases for the effects of urbanization on climatic variables, as explained by Crawley (2008).

In the ambit of climatic analyses, the role of days representative of different typical conditions of the year stands out. From the analysis of climate variables (Step 1), the goals for environmental adequacy and consequent passive project strategies are established (Steps 2 and 3 of Climatic Analysis).

From a thermal point of view, the goals of building adequacy involve the control of heat gains and losses, tending to the minimization of gains and maximization of losses in warmer climates and the opposite in the case of cooler ones. Additionally, capturing daylight under clear and overcast sky conditions is contemplated. In essence, six goals are hereby proposed, namely: (1) Minimization of solar gains; (2) Maximization of heat losses; (3) Maximization of solar gains; (4) Minimization of heat losses; (5) Capturing daylight under clear-sky conditions; and (6) Capturing daylight under overcast-sky conditions. To each of these goals, a set of strategies for the architectural design-project is associated.

For the goal of Minimization of solar gains, for instance, the following strategies were associated: shading, radiation reflection, thermal inertia, and thermal insulation. For the goal of Capturing daylight under clear- and overcast-sky conditions, access of solar radiation (global or simply diffuse) originating from the sky and the surroundings, through direct transmission (transparency) and through reflection, was suggested.

The complete listing of the six goals and their respective strategies is presented in Figure 3. In total, there are ten proposed passive strategies for the architectural design-project, eight of which for thermal performance and two for capturing daylight, associated to the different goals of environmental adequacy, namely:

- For thermal performance: 1. Shading, 2. Reflection of solar radiation, 3. Thermal inertia, 4. Thermal insulation, 5. Natural ventilation, 6. Evaporative cooling, 7. Passive solar heating, and 8. Minimizing of exposure area to the exterior.
- For capturing daylight: Access of solar radiation (global or simply diffuse) through 9. Direct transmission, and/or 10. Though reflection.

A single strategy may be adopted in opposite goals of environmental adequacy, for example, thermal inertia, which applies to both the minimization of solar gains (for projects in warm climates) and maximization of their harnessing (for projects in cooler climates). Other strategies are specific to a given goal, such as shading, for the minimization of solar gains, and passive solar heating, for the goal of maximizing such gains.

At the end of this stage, preliminary understanding of climate as resource for the formulation of premises of the design concept is reached.

Givoni (1969), in his proposal for the Bioclimatic Zoning, indicated a set of strategies for the climatic insertion of the architectural design which are, nevertheless, exclusively associated to the conditions of temperature and humidity, namely: passive heating, natural ventilation, thermal mass, thermal insulation, and evaporative cooling. In the presented methodological proposal, shading, minimization of exposure area to the exterior (a form strategy dealing with how compact the internal space is), and strategies regarding daylight access, not included by Givoni (1969), which considers the internal environment already protected from global radiation, are added. It is important to point out that this proposal does not aim to replace Givoni's (1969) recommendations, but rather lean on the strategies associated to such zoning, adding a more thorough reading of the climate conditions in question and the respective potential design strategies.

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[1] TMY - *Test Meteorological Year* is an annual climate database for a given area, resulting from the compilation of monthly hourly data, originating from different years, without considering records of extreme temperature, generating a hypothetical climatic year (LABEEE, 2005).

Identificação de máximas, mínimas e médias horárias de temperatura, diárias e mensais
Identification of daily and monthly maximum, minimum and average temperatures

Identificação de máximas, mínimas e médias horárias de umidade, diárias e mensais
Identification of daily and monthly maximum, minimum and average humidity levels

Identificação do regime mensal dos ventos predominantes, incluindo velocidade e direção
Identification of the monthly regime of prevailing winds, including speed and direction

Identificação das condições de céu ao longo do ano (dados de nebulosidade) e médias horárias mensais de iluminância
Identification of sky conditions throughout the year (cloudiness data) and hourly average illuminance levels per month

Identificação das máximas radiações horária diária e acumulativa mensal, no plano horizontal e nas 8 orientações
Identification of maximum daily hourly radiation and maximun monthly cumulative radiation, in the horizontal plane and in the 8 orientations

Amplitude térmica de dias representativos e mensal
Diurnal Temperature variation of representative days and monthly
Significativa em clima quente e seco, onde a inércia térmica é uma estratégia-chave
Significant in hot and dry climate, where thermal inertia is a key strategy

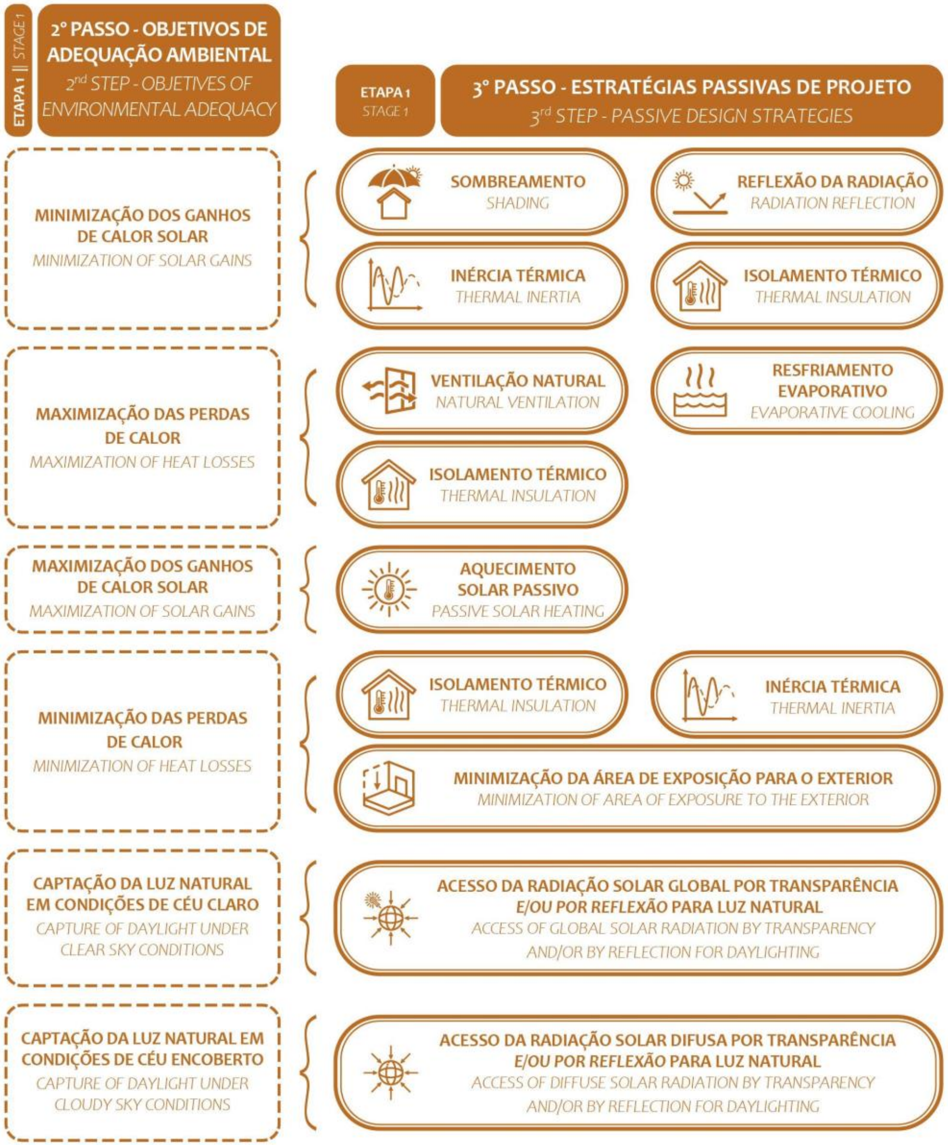
Relação entre temperatura e umidade ao longo dos meses
Relation between temperature and humidity levels over the months
Significativa em clima quente e úmido, onde a umidade pode comprometer o conforto térmico, e em clima quente e seco, onde o resfriamento evaporativo é uma estratégia-chave
Significant in hot and humid climate, where humidity can compromise thermal comfort, and in hot and dry climate, where evaporative cooling is a key strategy

Relação entre dados de temperatura e vento
Relation between temperature and wind figures
Significativa em clima quente e úmido onde a ventilação natural é uma estratégias-chave
Significant in hot and humid climate where natural ventilation is a key strategy

Relação entre dados de temperatura e radiação global
Relation between temperature data and global radiation
Significativa em climas temperado e frio, onde o aquecimento solar passivo é uma estratégia-chave, e em clima quente, onde o sombreamento é uma estratégia-chave
Significant in temperate and cold climates, where passive solar heating is a key strategy, and in hot climate, where shading is a key strategy

Relação entre radiação direta e difusa ao longo dos meses
Relation between direct and diffuse radiation over the months
Significativa em clima quente, onde o sombreamento é uma estratégia-chave. Importante também para definir as estratégias de captação da luz natural em todos os tipos de clima
Significant in hot climate, where shading is a key strategy. Also important for defining strategies for capturing daylight in all types of climate

Figure 2 - Analysis of Climatic Variables, including the description of their interrelations, which constitutes Step1 of Stage 1 of Climate Analysis. Source: The authors.



MINIMIZAÇÃO DOS GANHOS DE CALOR SOLAR
MINIMIZATION OF SOLAR GAINS
- **SOMBREAMENTO** SHADING
- **REFLEXÃO DA RADIAÇÃO** RADIATION REFLECTION
- **INÉRCIA TÉRMICA** THERMAL INERTIA
- **ISOLAMENTO TÉRMICO** THERMAL INSULATION

MAXIMIZAÇÃO DAS PERDAS DE CALOR
MAXIMIZATION OF HEAT LOSSES
- **VENTILAÇÃO NATURAL** NATURAL VENTILATION
- **RESFRIAMENTO EVAPORATIVO** EVAPORATIVE COOLING
- **ISOLAMENTO TÉRMICO** THERMAL INSULATION

MAXIMIZAÇÃO DOS GANHOS DE CALOR SOLAR
MAXIMIZATION OF SOLAR GAINS
- **AQUECIMENTO SOLAR PASSIVO** PASSIVE SOLAR HEATING

MINIMIZAÇÃO DAS PERDAS DE CALOR
MINIMIZATION OF HEAT LOSSES
- **ISOLAMENTO TÉRMICO** THERMAL INSULATION
- **INÉRCIA TÉRMICA** THERMAL INERTIA
- **MINIMIZAÇÃO DA ÁREA DE EXPOSIÇÃO PARA O EXTERIOR** MINIMIZATION OF AREA OF EXPOSURE TO THE EXTERIOR

CAPTAÇÃO DA LUZ NATURAL EM CONDIÇÕES DE CÉU CLARO
CAPTURE OF DAYLIGHT UNDER CLEAR SKY CONDITIONS
- **ACESSO DA RADIAÇÃO SOLAR GLOBAL POR TRANSPARÊNCIA E/OU POR REFLEXÃO PARA LUZ NATURAL** ACCESS OF GLOBAL SOLAR RADIATION BY TRANSPARENCY AND/OR BY REFLECTION FOR DAYLIGHTING

CAPTAÇÃO DA LUZ NATURAL EM CONDIÇÕES DE CÉU ENCOBERTO
CAPTURE OF DAYLIGHT UNDER CLOUDY SKY CONDITIONS
- **ACESSO DA RADIAÇÃO SOLAR DIFUSA POR TRANSPARÊNCIA E/OU POR REFLEXÃO PARA LUZ NATURAL** ACCESS OF DIFFUSE SOLAR RADIATION BY TRANSPARENCY AND/OR BY REFLECTION FOR DAYLIGHTING

Figure 3 - Set of Goals of Environmental Adequacy and the resulting Passive Design Strategies, which constitute Steps 2 and 3 of Stage 1 of Climate Analysis, respectively. Source: the authors.

As previously referenced, architectural design parameters are determinant of buildings' climatic insertion. Out of such parameters, the following stand out: form and its relation to solar orientation, composition, and façade treatment (including shading strategies), thermophysical characteristics of building components, design of openings for daylight access and natural ventilation. Other parameters associated to the specification of the building's envelope and to be considered in the analyses of architectural environmental adequacy are: air infiltration and dynamic control for both opening for ventilation and external shading elements, as well as thermal insulation of transparent areas (also known as night-shutters and applicable for the minimization of heat losses by glazed areas, specially at night, after the period for solar radiation harnessing for passive solar heating).

The influence of each of these internal environmental conditions is explained by fundamentals of physics applied to the architectural design and by the resulting principles of the bioclimatic approach for architecture, explained in a series of bibliographic references (FROTA; SHIFFER, 2004; GIVONI, 1994; OLGYAY, 1963; SZOKOLAY, 2004).

Elaboration of the base-case and alternative scenarios

Aspects of use and occupancy may also characterize the base-case and generate assessment scenarios, considering variations in internal heat gains and patterns of thermal and light comfort. However, for the purpose of simplification, variations of these aspects are not contemplated by this proposal, despite being easily included in analytical studies.

The correspondence between the ten passive strategies in Stage 1 and the most relevant parameters for their influence are shown in Figure 4. The set of parameters defines the elaboration of the so-called base-case, which composes the model for the creation of the respective alternative scenarios for the passive strategies' efficiency verification, in the context of the environmental adequacy goals for the project's thermal and lighting performance.

As in the case of passive strategies for the environmental adequacy goals, some of the proposed parameters serve more than one strategy. The form parameter, for instance, is applicable for the strategies of shading, thermal insulation, thermal inertia, natural ventilation, passive solar heating, and capture of global solar radiation for daylighting. Taking another example, the U value factor (Global Thermal Transmission Coefficient) applies to thermal insulation as well as passive solar heating, while others are exclusive to a single strategy, such as the building's thermal capacity, which falls into parameters of thermal inertia.

The value of geometric simplified base-cases is in the fact that the focus of these studies in of the comprehension of physics phenomena linked to a given strategy and to a project parameter and not on the specific architectural solution.

The definition of the base-case and the variation of its parameters depends on the specific goals of environmental adequacy. For instance, the assessment of the advantages of shading for the minimization of heat gains begins with the verification of the impact of solar radiation on an internal space's thermal conditions, which may be done with the testing of a rectangular-shaped simplified model, with a single exterior façade, initially without shading element, to which performance simulations aiming for the quantification of solar heat gains are done for each of the main orientations (north, south, east, and west, and may include northeast, northwest, southeast, and southwest).

In a second round of simulations, the test model is simulated with the insertion of shading elements. The results of both simulation rounds are then compared. Other simulations may be done for the verification of variations of the illuminating area on solar gains.

There is yet the situation of base-cases with more than one exterior-exposed face, such as spaces modeled for cross ventilation and bilateral access of daylight, or with openings on the roof level. An option for the definition of base-cases dimensions, recommended for the architectural performance models with more than one exposed face, is following the project guidelines known as Practical Performance Rules (Rules of Thumb), including light and/or ventilation efficiency (CIBSE, 2005). These guidelines establish proportions between the internal space's depth and height. Thus, the base-case originates from conditions favorable to daylight access and natural ventilation.

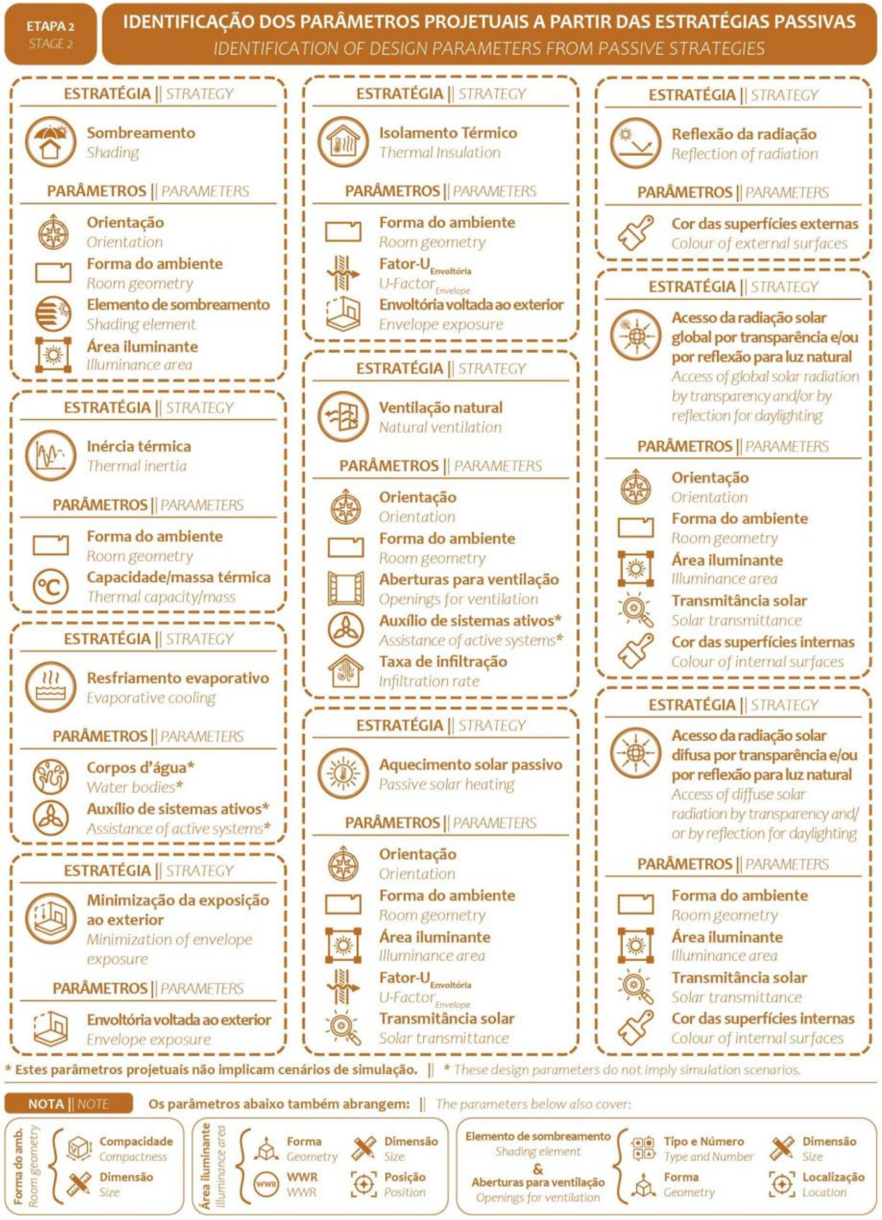


Figure 4 - Stage 2: Elaboration of the Base-Case, including the Identification of Design Parameters, the Elaboration of the Base-Cases themselves and of Alternative Scenarios, from the selection of passive strategies done in the previous stage. Source: the authors.

For the project-design issues in which illumination constitutes one of the priorities among the performance requirements, the definition of the base-case for the thermal analytical studies must initially consider the recommendations of the practical design rules for capturing daylight. On the other hand, natural ventilation also has its own practical design rules for the project's starting point. As a general rule, considering the global environmental performance (thermal and luminous), the formulation of the base-case for the analytical studies must prioritize the more restrictive rules and guidelines.

In sum, base-cases analytical studies are an extension of the understanding of the potentials and the limitations of climate for architectural environmental performance, as well as the possible site-planning situations, with the possibility of incorporating the effects of orientation and surrounding obstructions, regardless of any architectural preconception. It is important to point out that such studies do not refer to the verification of final design solutions, but to the understanding of each parameter's role in the process of environmental adequacy in architecture. Once again, it is worth mentioning that the proposed relationship between environmental adequacy general goals, passive strategies, and architectural parameters to be explored in the base-case is based on the fundamentals of physics applied to the environmental performance of architecture.

Analytical performance studies: sensitivity analyses, combinatorial scenarios, and cumulative solutions

Regarding the insertion of architectural parameters in the design process, all those listed here (from building form to operture size) are susceptible to parametrization, i.e., may have their fundamental characteristics regulated by value intervals, to test and optimize their impact on the response of one or more of the project's environmental performance issues.

In this stage, the base-case scenarios are initially tested through sensitivity analyses, which are the process through which each parameter's performance and their possible variations is individually assessed, possibly related to dimensions, specifications, or form, while all remaining parameters of the study model are kept equal. Subsequently to the sensitivity analyses, the development of design guidelines for better environmental performance leads to the verification of the effect of the project's set of parameters.

In many cases, a building's environmental adequacy is associated with the multicriteria optimization of each factor of the architectural designproject. Regarding the project of shading elements, for example, the most appropriate solution is the one which controls the undesirable impact of global radiation for a given context, but which still maintains adequate daylighting.

To illustrate, Figure 5 proposes scenarios for the impact of the sensitivity analysis of four design parameters in a base-case's thermal conditions: orientation, form, illuminating area, and shading elements. In this moment, the analyses aim to quantify the advantages of project resources for the exercise of the shading strategy, as one of the means of minimizing the heat gains, exclusively.

The same figure presents the adopted parameters for the elaboration of the base-case. For the first three (orientation, form, and illuminating area), three variations in relation to the base-case are suggested. While six suggestions are made for the shading parameter: three for the horizontal-type element, and three for the vertical-type one.

Similarly, scenarios to the parametric sensitivity analysis, associated to the six objectives proposed here to the environmental adequacy of the architectural design project at conceptual stage, are presented in figures 6a to 6f, encompassing the complete set of parameters related to the passive strategies, particular to each objective.

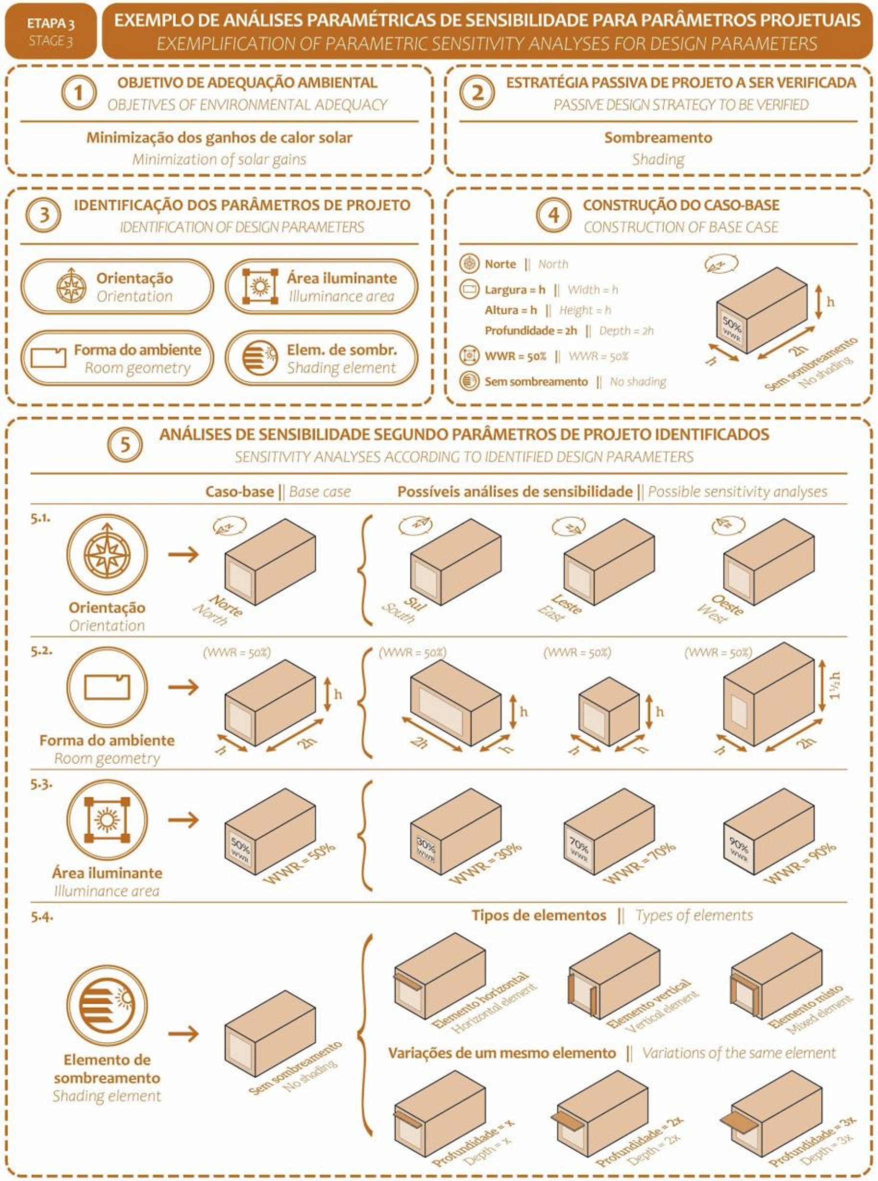


Figure 5 - Exemplification of Stage 3: Parametric Sensitivity Analyses for Design Parameters, with suggested scenarios for the parametric analyses of four design parameters: orientation, form, illuminating area, and shading elements, in order to fulfill the shading strategy, as one of the resources for the specific goal of Minimization of the Solar Gains. Source: The authors.

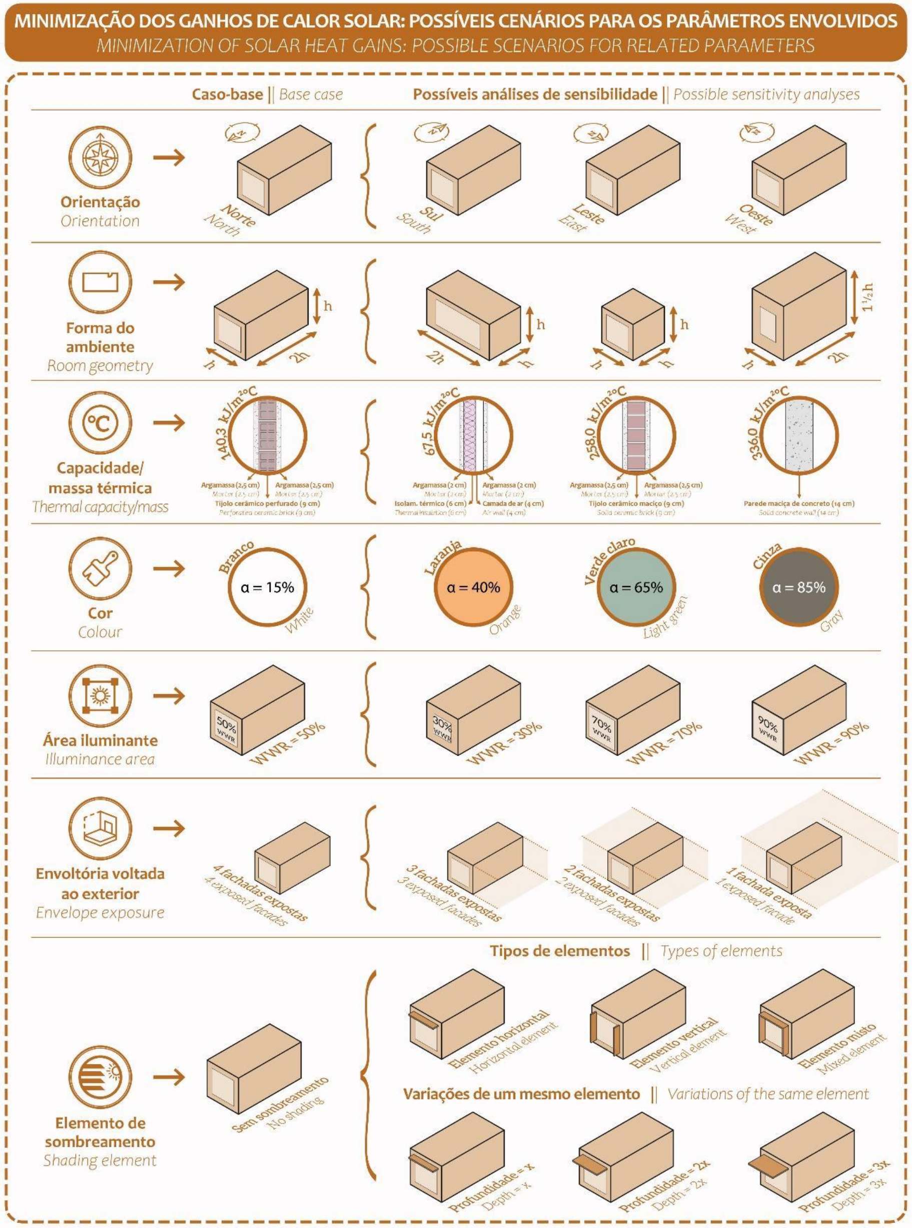


Figura 6a - Scenarios forParametric Sensitivity Analysis for the goals of Minimization of Solar Gains. Source: The authors.

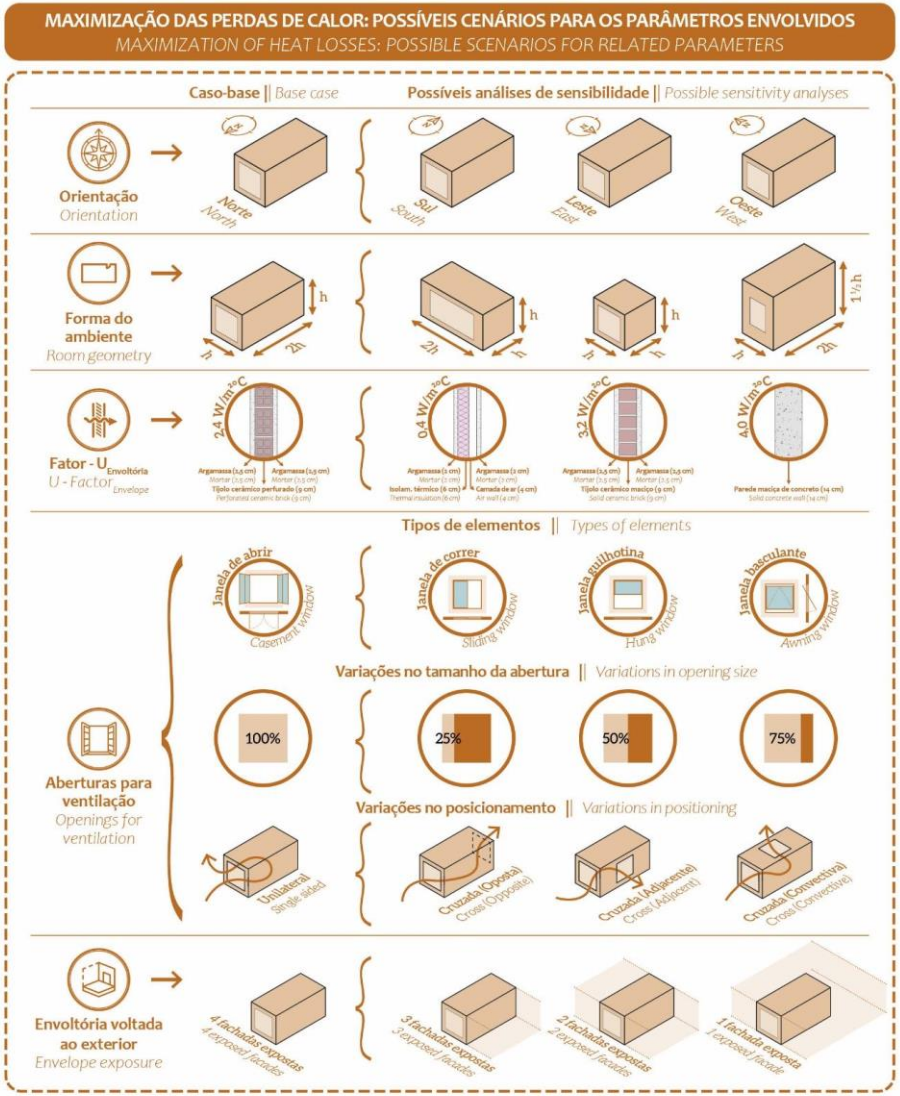


Figura 6b - Scenarios of Parametric Sensitivity Analysis for the goal of Minimization Heat Losses. Source: The authors.

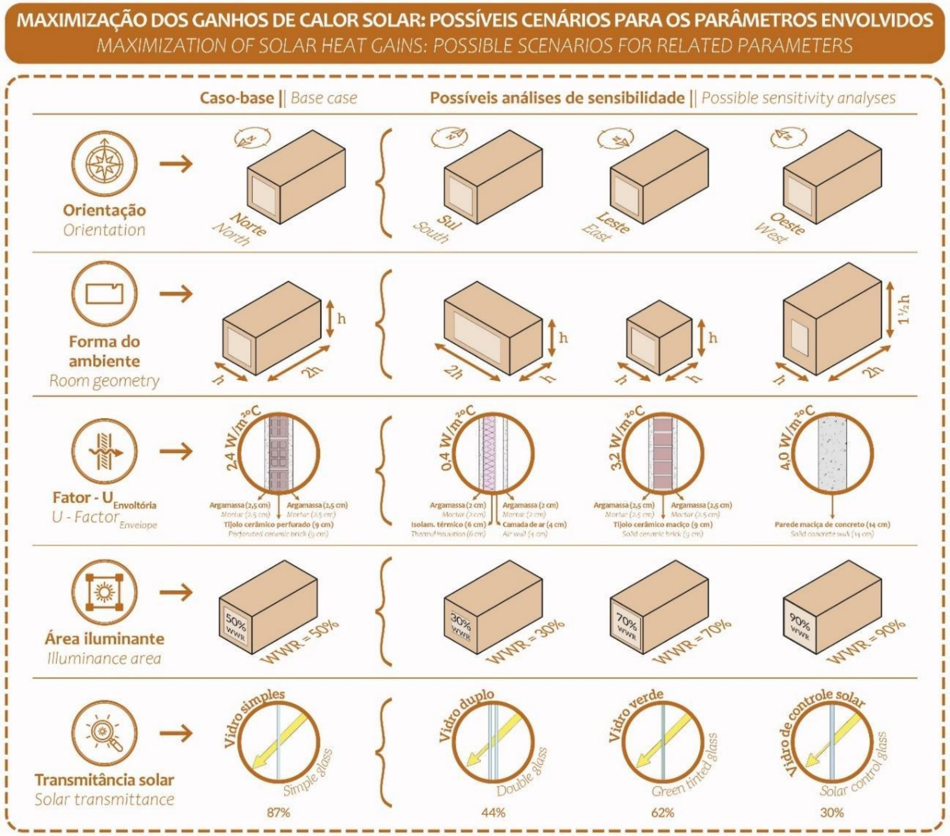


Figura 6c - Scenarios of Parametric Sensitivity Analysis for the goal of Maximization of Solar Heat Gains. Source: The authors.

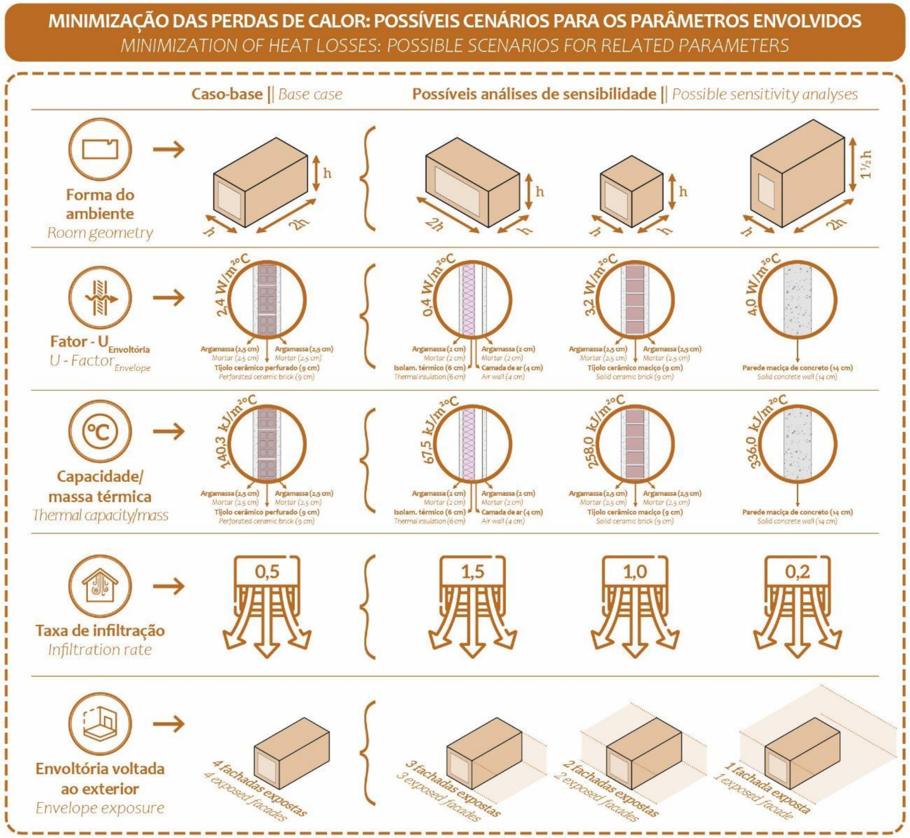


Figura 6d - Scenarios of Parametric Sensitivity Analysis for the goal of Minimization of Heat Losses. Source: The authors.

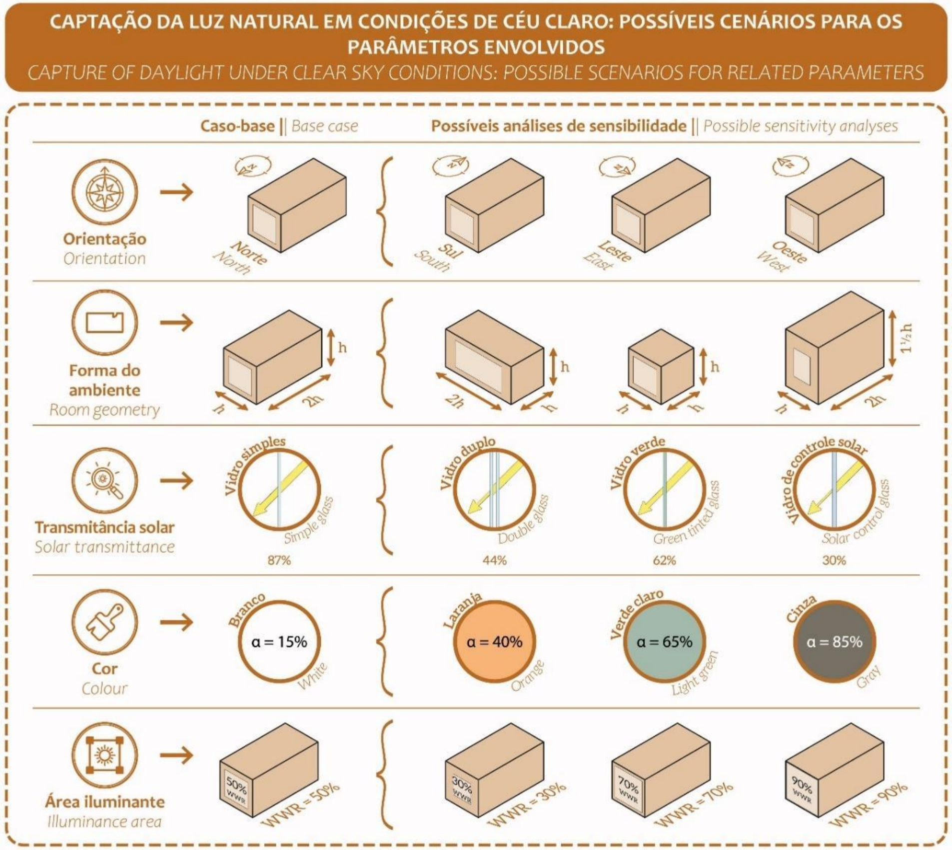


Figura 6e - Scenarios of Parametric Sensitivity Analysis for the goal of Capturing Daylight Under Clear Sky Conditions. Source: The authors.

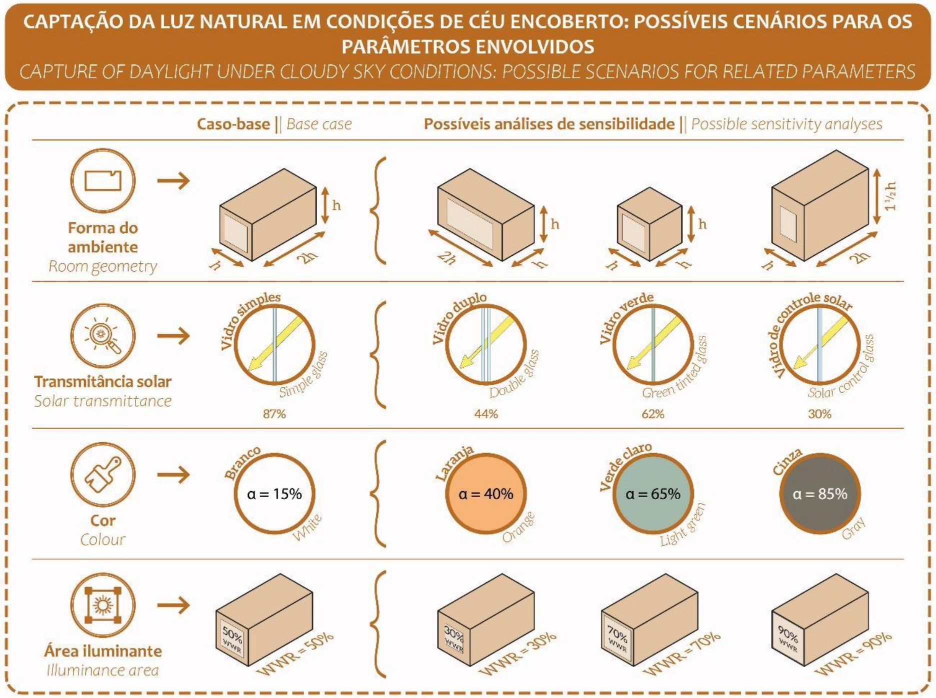


Figura 6f - Scenarios of Parametric Sensitivity Analysis for the goal of Capturing of Daylight Under Cloudy Sky Conditions. Source: The authors.

The recommended performance indicators for the sensitivity analyses of the six environmental adequacy goals that define this methodological proposal may concern hourly, monthly, and annual data. For the goals related to the project's thermal performance, the following data are included: temperature, annual hour percentage of comfort and discomfort due to cold and heat, as well as daily, monthly, and annual residual cooling and/or heating load totals, depending on the climatic context and the related environmental adequacy goal. In parallel, hourly values of solar radiation incurring on the model's envelope and/or the internal space throughout a day, and monthly or annual totals, as well as the difference between interior and exterior maximum temperatures, and air-change rates (indicative of natural ventilation), are quantitative data that assist in the interpretation and general understanding of the main performance indicators.

Table 1. Performance indicators chart for environmental adequacy for the parametric sensitivity analyses. Source: The authors.

OBJETIVOS ***GOALS***	**INDICADORES DE DESEMPENHO PARA A ADEQUAÇÃO AMBIENTAL** ***PERFORMANCE INDICATORS FOR ENVIRONMENTAL COMPLIANCE***	
Minimização dos ganhos de calor solar (1) e Maximização das perdas de calor (2) *Minimizing solar heat gains (1) and Maximizing heat losses (2)*	- Para uma determinada condição de conforto: **Horas anuais de conforto e de desconforto por calor**, em %; - Para uma determinada condição de conforto: **Carga residual de resfriamento**, em kWh/m^2 por dia, mês e/ou ano; - **Radiação incidente na envoltória e/ou no ambiente interno**, em kWh/m^2 por dia, mês e/ou ano; e - Para os meses mais quentes do ano: **Temperatura interna máxima (TO) e o Δt correspondente entre temperatura interna e externa**, em °C. - Para uma ou mais semanas típicas e, ou representativas das condições climáticas do lugar: **Perfil horário de Temperatura do Ar e temperatura Operativa e valores de Umidade Relativa.**	*- For a given comfort condition:* ***Annual hours of comfort and discomfort due to heat****, in%;* *- For a given comfort condition:* ***Residual cooling load****, in kWh/m^2 per day, month and/or year;* *-* ***Solar radiation on the envelope and/or indoors****, in kWh/m^2 per day, month and/or year; and* *- For the hottest months of the year:* ***Maximum internal temperature (TO) and the corresponding Δt between internal and external temperature****, in °C.* *- For one or more typical and/or representative week of the local climatic conditions:* ***Hourly profile of Air Temperatures, Operative Temperatures and Relative Humidity values.***
	NOTA 1: Os indicadores de horas anuais de conforto e carga residual de resfriamento substituem um ao outro. A escolha do indicador mais apropriado vai depender do objetivo da análise de desempenho. **NOTA 2:** Para os casos das perdas de calor por efeito da ventilação natural, cabe destacar a importância da Taxa de renovação do ar (N), como mais um indicador de desempenho. **NOTA 3:** Para os climas do tipo quente-úmido, vale verificar os valores horários de Umidade relativa (UR) e Umida absoluta, em especial nos horários de temperaturas máximas. A mesma consideração se aplica para a velocidade do ar (m/s).	***NOTE 1:*** *the hourly and annual indicators of thermal comfort and residual loads replace each other. The most appropriate indicator will depend on the objective of the performance assessment.* ***NOTE 2:*** For the case of heat loss through natural ventilation, it is worth mentioning the importance of Air-Change rates as another performance indicator. ***NOTE 3:*** *For warm and humid climates, it is worth verifying typical daily the values* of relative and absolute humidty, specially during the hours of peak temperature. The same consideration is applicable to air speed (m/s).
Maximização dos ganhos de calor solar (3) e Minimização das perdas de calor (4) *Maximizing solar heat gains (3) and Minimizing heat losses (4)*	- Para uma determinada condição de conforto: **Horas anuais de conforto e de desconforto por calor**, em %; - Para uma determinada condição de conforto: **Carga residual de aquecimento**, em kWh/m^2 por dia, mês e/ou ano; - **Radiação incidente na envoltória e/ou no ambiente interno**, em kWh/m^2 por dia, mês e/ou ano; e - Para os meses mais frios do ano: **Temperatura interna máxima (TO) e o Δt correspondente entre temperatura interna e externa**, em °C. - Para uma ou mais semanas típicas e, ou representativas das condições climáticas do lugar: **Perfil horário de Temperatura do Ar e Temperatura Operativa e valores de Umidade Relativa.**	*- For a given comfort condition:* ***Annual hours of comfort and discomfort due to heat****, in %;* *- For a given comfort condition:* ***Residual heating load****, in kWh/m^2 per day, month and/or year;* *-* ***Solar radiation on the envelope and/or indoors****, in kWh/m^2 per day, month and/or year; and* *- For the coldest months of the year:* ***Maximum internal temperature (TO) and the corresponding Δt between internal and external temperature****, in °C.* *- For one or more typical and/or representative week of the local climatic conditions:* ***Hourly profile of Air Temperatures, Operative Temperatures and Relative Humidity values.***
	NOTA: Os indicadores de Horas anuais de conforto e Carga residual de aquecimento substituem um ao outro. A escolha do indicador mais apropriado vai depender do objetivo da análise de desempenho.	***NOTE:*** *the hourly and annual indicators of thermal comfort and residual loads replace each other. The most appropriate indicator will depend on the objective of the performance assessment.*

The calculation of the Maximum Indoor Dry Air Temperature or the Operational Temperature[2] (TO) and other associated variables, such as air-change rates and incurring values of solar radiation, may be obtained by means of simplified calculations (FROTA, 2005). For the remaining indicators, the use of thermodynamics computational tools is necessary.

For the study of naturally ventilated spaces, exclusively, the performance assessment dispenses the calculation of cooling and/or heating loads, being sufficient to look at temperatures and percentages of hours of comfort.

Equally, for the goals of daylight access , the suggested indicators refer to hourly data as well as monthly and annual percentages. The hourly data indicator is expressed by illuminance values calculated for typical and/or representative days of the year, and specific sky conditions. For the percentage values, the so-called Daylight Factor – DF (IES, 2018; MOON e SPENCER, 1942), Daylight Autonomy – DA (REINHART et al., 2006), and Useful Daylight Illuminance – UDI (NABIL; MARDALJEVIC, 2005) may be adopted. While the illuminance and DF calculations are more simplified, DA and UDI calculations require the use of methods of dynamic daylighting annual simulation (Climate Based Daylight Modelling – CBDM) (REINHART; HERKEL, 2000).

In the case of daylighting analyses, UDI calculation may replace those of DF and DA. On the other hand, DF calculation provides an immediate understanding of the performance tendency in the modelled space, i.e., whether the architectural concept proposal tends to a more or less well-lit environment, foregoing a more meticulous analysis in the design stage. At the same time, calculation of illuminance throughout the day reveals a quality aspect to which the occupant is exposed, and which is not equally expressed by percentage indicators. The complete set of indicators and their units for the sensitivity analyses stage is presented in Table 1, in the indicator chart.

It is worth mentioning that the suggestion of thermal and luminous indicators to be extracted from technical studies (such as Operational Temperature, Daylight Factor, Useful Daylight Illuminance, and others) is not accompanied by references to

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[2] Operational Temperature (TO), also known as resulting temperature, may be defined as the average between the average radiant temperature of internal surfaces and air temperature, weighted by the respective heat transference coefficients (ASHRAE, 2017).

performance targets, since those depend on the climate in question and on project variables, such as use and occupancy.

Since such studies do not refer to a final architectural solution, but rather to conceptualdesign speculations, the importance of quantifying the solutions' performance in this early project and analysis stage falls upon the comparative differences between scenarios rather than on the absolute results.

An example of parametric sensitivity analysis is seen on the studies by Bhatla and Gonçalves (2012), in which the cooling loads reductions of a residential unit's simplified model, north-south-oriented, in the Indian city of Madras (Lat. 13°N), in hot and humid weather, resulting from the prolongation of an external horizontal protection, are compared. Varying from 1 to 3 meters in depth, the studies revealed that the first meter of shading wields a significant effect on the reduction of the internal thermal loads, nevertheless, such impact is less relevant for each added meter of shading (Figure 7).

Subsequently, the work compared the benefit of shading versus that of enclosure thermal insulation and it verified that shading results in around 32% reduction of cooling loads, compared with the base-case with no solar protection, in contrast to 37% attained by the introduction of insulation, in the aforementioned climate context. Advancing to the stage of verification of the cumulative effect of both strategies (shading and thermal insulation), thermodynamics simulations indicated a nearly 50% potential reduction on the base-case's thermal loads.

The results of the sensitivity analyses subsidize the elaboration of subsequent scenarios, in which the joint contribution of the project's parameters is perceived. In the analytical study of such scenarios, it is strategic to verify the step-by-step contribution of the multiple parameters (already optimized or improved in the previous stage), from the one with greater impact to the one with least impact. Although the order of the factors does not alter the model's final performance result, this methodological approach enables gauging the relative and optimized importance of each parameter for the model's performance. Such hierarchization is informed by the results of the sensitivity analyses. Lastly, the elaboration of design guidelines for environmental adequacy entails the verification of the cumulative effect of the set of strategies.

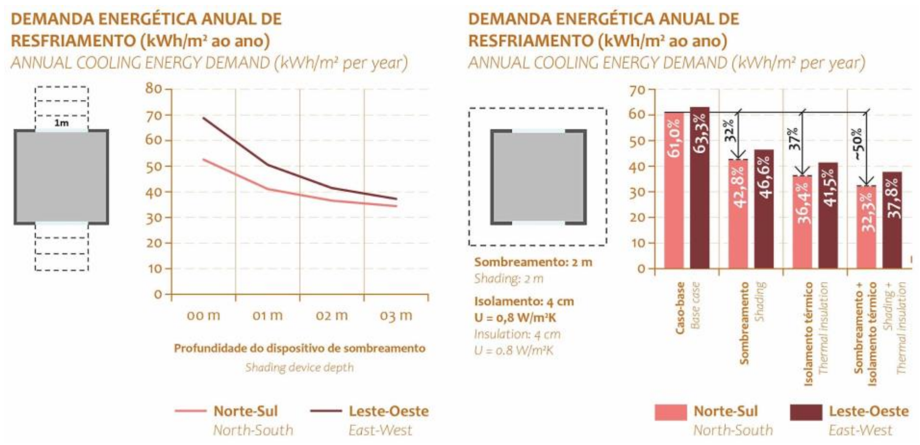

Figure 7 - To the left, parametric sensitivity analysis of the impact of different depth solar protections on the cooling thermal load in the residential unit in the city of Madras, in India. To the right, calculation of the impact of different degrees of shading versus the insertion of thermal insulation on the cooling loads in the residential unit, compared to the cumulative effect on shading and thermal insulation. Source: Bhatla and Gonçalves (2012).

In the assessment process of the base-cases' thermal and lighting issues, the combination of multiple alternatives of different design parameters opens an range of distinct architectural possibilities, from which a set of them with similar performance may be taken and, potentially, appropriated for a desirable architectural solution. An example of application of such analytical approach is what was done in the design process of the headquarters of French education and research institution Toulouse School of Economics – TSE, in the city of Toulouse, which had parametric studies of combinatory scenarios for façade solutions in the architectural conception stage, including the verification of the impact of the parameters of glazed area and shading elements (BODE, 2015).

Considering the characteristics of subtropical temperate and humid climate of the city of Toulouse, the project of the TSE building was directed for solutions against the impacts of solar radiation in the warm periods of the year, without losses to daylighting. Analytical assessment studies cooling loads and daylight accessed examined the effect of alternatives for the façade design, composed of three variations of glazed area (window wall ratio – WWR): 30%, 50%, 70%; and two types of solar protection: one with vertical perpendicular fins, and the other with the same vertical fins at a 45º angle (increasing shading efficacy without enlarging to the vertical element), adding the option of absence of shading, resulting in nine assessment scenarios (Figure 8).

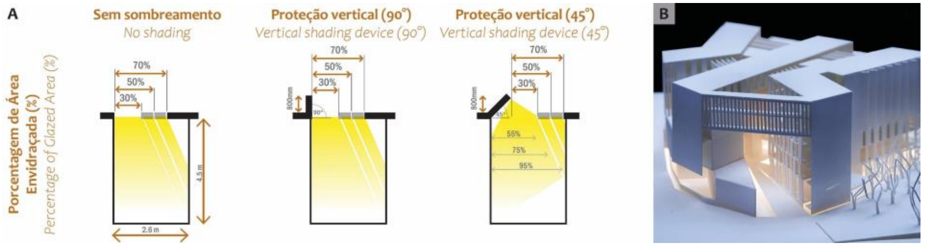

Figure 8 - (A) Combination of window size (WWR de 30%, 50% e 70%) and types of shading, for the TSE building project. (B) Digital model of the building. Source: Images granted by the building services engineering and environmental consulting company BDSP Partnership. Edited by the authors.

The vertical type of external solar protection applied to all orientations was previously defined by the architectural intentions for the general formal expression of the project's intention. Methodologically, the test alternatives for the façade configuration were composed of combinatory analyses of the pre-established options of glazed area and shading type, in order to solve a multicriterial performance problem, with a comparative analysis of the results. The nine scenarios were then tested on the seven floors of the ten façades of the project's three rectangular multifaceted blocks, including exterior-facing façades and interna patios. The best performing alternatives for each floor on each façade varied as a result of exposure to global solar radiation, resulting from orientation and degree of external obstruction associated with the surrounding, as well as architectural form itself.

To illustrate, the simulation results for DF and for cooling loads associated with the artificial climatization for the 2nd and 5th floors, on the ten project façades, are shown in the sequence (Figure 9). The simulations show the benefit of decreasing the glazed area and increasing shading, with the increase of exposure to global radiation. It is also possible to observe a more significant impact of the obstruction on DF values than on energy demand for climatization. Regarding the daylight access, the scenarios with 30% glazed area fall short of the performance goal but are close to it without the shading. The scenarios with 50% glazing, with and without shading, perform the best, in general. On the other hand, the façades with 70% of glazed area surpass the goal in most cases, even with external shading. The difference between scenarios is smaller in the studies of thermal loads.

In short, the most adequate solutions for each floor and orientation were selected according to the smallest cooling loads and lighting energy demand for the best daylight access. In parallel, to reconcile the quantitative recommendations for the building's thermal and luminous performance and the initial architectural intentions of façade formal unity, the recommendations were grouped in floors and orientations (Figure 10).

As final project result, the employed guidelines were: for the first two floors – glazed façade area (WWR) equal to 70%, without external solar protection surrounding all orientations; for the third and fourth – smaller glazed area, 50%, also without external protection for all orientations; for the top three floors – 30% glazed area, either without external protection, or with vertical protection, perpendicular to the façade or inclined, according to the degree of exposure to global radiation. This is an example of final architectural solution that presents a variation of façade treatment, adapted to the most favorable conditions of environmental performance, instead of adopting an optimal solution for each case of orientation and height.

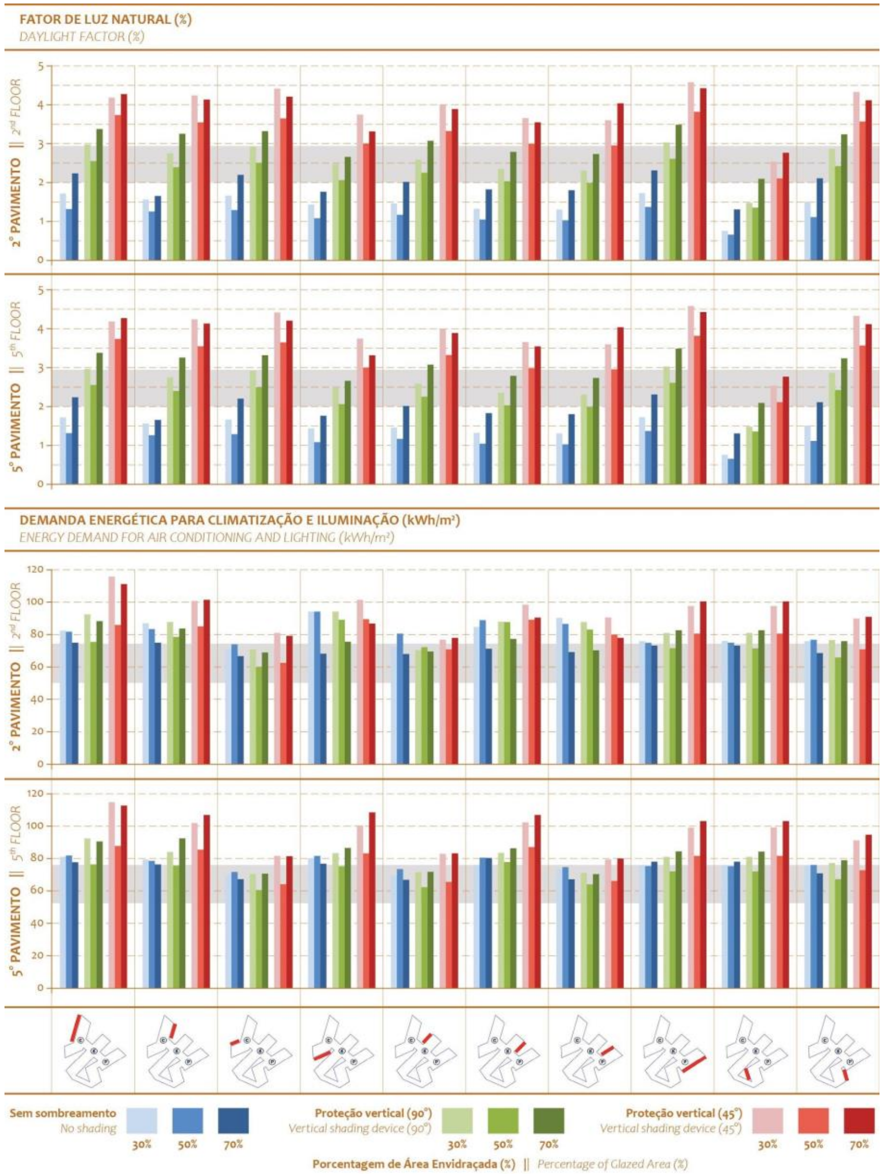

Figure 9 - Results of DF (Daylight Factor) and annual artificial climatization energy demand (mainly cooling loads) and artificial lighting (kWh/m^2 yearly) for the 9 façade scenarios on the 2nd and 5th floors, in the building's ten façades. The performance goals are highlighted by the gray stripe. Source: Images granted by the building services engineering and environmental consulting company BDSP Partnership. Edited by the authors.

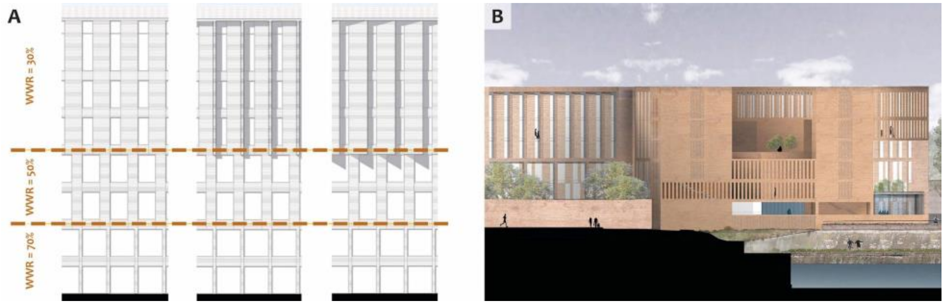

Figure 10 - (A) Generalization diagram of the façade strategies for the building's 7 floors. (B) Digital model of the building. Source: Images granted by the English system engineering and environmental consulting company BDSP Partnership. Edited by the authors.

Final considerations

The analytical procedures developed by means of computer simulations facilitate the verification and the refinement of architectural solutions, allowing not only the indication of "optimal" solutions from an environmental and energy point of view, but also opening a range of adequate solutions.

Following this approach, the herein-presented methodological proposal for the application of parametric procedures in the process of architectural conception stems from a set of environmental adequacy goals, related to local climate, to which passive strategies for thermal and luminous performance are associated. In this context, a series of analytical studies, including the verification of design parameters and architectural strategies, is proposed for the investigation of the impact of basic parameters of the architectural design-project, regarding thermal and luminous performance in an internal space. Such analyses facilitate the comprehension of each design parameter's role in the initial performance of the architectural conception base-case and its variations. Going forth to the analysis of cumulative-solution scenarios, the optimization of parametric models is obtained. Alternatively, the study of combinatory-solution scenarios offers a set of options adequate to the project's performance. In the end, the set of results from the multiple stages of analytical procedures gathers project guidelines for the environmental adequacy of architecture.

In the ambit of architectural conception, the simplicity of the base-case is a key factor, so the numeric results obtained in computer simulations are easily linked to the model's architectural parameters, contributing to the indication of specific project guidelines, as seen in the works by Bhatla and Gonçalves (2012) and Bode (2015). Thus, the purpose is to deepen the understanding of the design parameters' impact on architecture's environmental adequacy, surpassing the generality of climate diagnosis and, consequently, providing more specificity to the project strategies as early as the conception stage. Therefore, instead of a corrective role of pre-defined solutions, the results of analytical procedures feed the architecture project's creative stage with information on the potential of a set of passive strategies established for the project's thermal and luminous (daylight) performance.

With such analyses, an initial quantification of the effects of concepts and project-defining fundamental ideas is obtained, to inform the generation of the form and the detailing of the remaining project parameters. In summary, a methodological contribution is proposed for a cultural change in the architectural conception process, based on a deep understanding of the climate conditions in which the building is located and on the potential of passive strategies for architecture's environmental adequacy.

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