Architecture and Context: A Data-based Approach to Optimize Climate Performance of Built Facades

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Abstract. The present research stems from a critical reflection about the environmental adaptability of existing building envelopes. The main goal is to explore how to balance environmental optimization with contextual constraints, using modularity, flexibility and mass customization as guiding principles. An application study was carried out with the development of a second skin proposal aligned with the use and context of the building under study. For this purpose, simulations that assess environmental conditions were developed within a visual programming tool, not only feeding the design process with essential information, but also providing a flexible creative process. Results show that such simulations allow the designer to interpret these studies more accurately, reducing the iterative guesswork, since in this workflow it is possible to transform these outputs into proposition parameters for new designs or interventions.

Keywords: Data-driven analysis, Parametric facade design, Thermal performance, Mass customization, Second skin.

1 Introduction

New constructive and financial demands have been positively impacting the adoption of sustainability as a design parameter in Latin America. Good performance, be it constructive, energetic or financial, has become a rule that is not restricted to the design phase, as it can be applied to an object which is already consolidated. It is urgent indeed to think about sustainability beyond new buildings, seeking to improve the performance of buildings that already exist by enhancing occupants' comfort conditions, as well as reducing the energy impact that results from use.

Monteiro et al. (2015) discuss the concept of adaptive architecture at the intersection between buildings' characteristics, natural climate variations and the capability of human beings to adapt themselves and their environment. According to the authors, the built environment tends to perform better when conditioning strategies, preferably passive, provide for a certain interaction with users. This dialogue can take place in a more active way, e.g. with physical changes in the envelope, or interpretive, through the reorganization of internal uses.

Despite this growing trend, the production of hermetic buildings is still frequent, especially in work environments, where internal conditioning is disconnected from variations in the external climate, based on the dependence on HVAC systems (Gonçalves, 2015). This situation is sometimes a result of initial design decisions, such as facades oriented in an unfavorable direction for solar radiation and air flow. In other cases, this disconnection derives from disadvantageous changes in the envelope – such as the implementation of glass curtains on balconies in a climate that requires facade shading.

On the other hand, contemporary design and production technologies have been providing greater precision in the analysis and synthesis design cycles of building envelopes, whether in new or reconfiguration situations, using resources such as parametric simulations, generative design, digital fabrication and machine learning. Combined with the expertise of specialists, these tools provide a more informed decision-making process, as shown by Bernal et al. (2020). In that paper, the authors pursued optimized daylighting maximization solutions with minimal energy consumption for three different scenarios, drawing a parallel between the initial solutions, developed by experts, and those developed with the parametric tool. The study demonstrated that:

The migration of the architecture from static to parametric relationships is not only updating the notion of design thinking but also questioning the autonomy and effectiveness of only making decisions relying on experience. The literature on design expertise states that experts can build an interpretation of the design problem without significant analyses. The results of the parametric analysis and the sensitivity analysis of the DoE samples from different design scenarios show that the intuitive process regularly underperforms recommendations from the systematic process. (Bernal et al., 2020, p. 438)

In architecture, mass customization aligns parametric design and digital fabrication (Kolarevic, 2005) – consequently an optimized facade design inserted into this workflow can result in several different components. It is essential, therefore, that the diversity generated along the design stage can be materialized according to locally available resources. Furthermore, modularity is a fundamental strategy in a mass customization process to achieve efficiency similar to that of mass production (Duray et al., 2000). It also provides greater flexibility for future changes, so the customization process does not need to be restricted to the initial setup (Leite & Celani, 2021).

The discussion about the insertion of digital manufacturing technologies in the Global South countries permeates academic and practical environments and, essentially, issues of a political, social and cultural nature (Scheeren & Sperling, 2018). Successful examples have demonstrated sensitivity to the convergence between those tools and local builders' knowledge, challenging the existing production relationships, towards a more horizontal practice (Borges, 2016; Scheeren & Sperling, 2018). The projects showcased at the Homo Faber exhibitions, in 2015 and 2018, illustrate fruitful approaches. The facade design by Frontis 3D for the Square 85 building, located in Bogota, Colombia, exemplifies the combination of parametric simulations and digital fabrication in the development of a second skin, focused on the environmental performance (Scheeren et al., 2018).

This research exists as a result of a critical reflection on the adaptability of constructed buildings, focusing on the facade layer. It seeks to understand how to adapt an existing building to local environmental conditions based on the optimization of its climatic performance, using guiding principles such as modularity, flexibility and mass customization to develop a second skin proposal aligned with the use and context of the building under study.

2 Methodology

The process scrutinized on this paper is the design of an adaptive facade, such being a performance-oriented artifact emergent from an array of parameters acting as design constraints. Design Science Research (DSR) eventually surfaced as an opportune approach, as it is precisely a scientific methodology concerned with the pragmatic research steps to the development of artifacts for solving specific human problems (Dresch et al., 2015), as opposed to less rigorous design processes more heavily reliant on intuitive decision-making and subjective output criteria that might end up being counterintuitive to the end-goal of the study.

Regardless, even with a more pragmatic and data-driven approach, designing still requires some degree of intuition. One of the challenges present in this framework is arriving at an output that reconciles intuitive design and the multi-criteria aspect of performance analysis. This multi-criteria approach invariably leads to some amount of compromise in performance in any given aspect being evaluated, since the design parameters that affect one output criteria positively often afford this gain at the expense of another that does not benefit from it. This being considered, the problems to be addressed are identified and configured into classes of hierarchical importance to make the employment of those parametric affordances more manageable.

Following this methodology, the facade is observed as an artifact that dialogues with external factors provided by the environment (Figure 1). Those external factors provide a myriad of phenomena that can be read as parameter inputs to be considered in this framework. The artifact itself is observed as an interface composed by a set of inner-working systems that processes those inputs, and the managing of those systems through design and iteration to arrive at an artifact that attains the closest to the desired array of outputs is the end-goal.

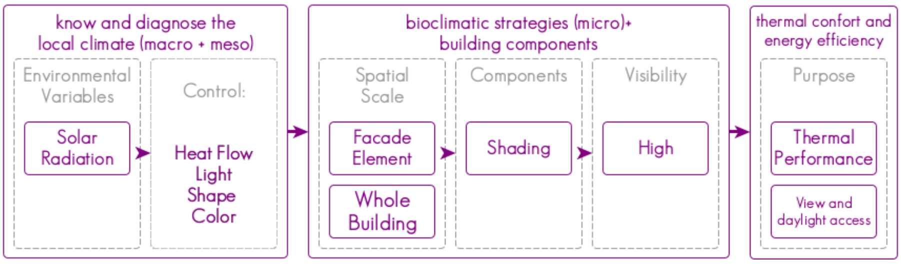

Figure 1. Initial characterization of the research workflow within a bioclimatic design framework. Source: Elaborated by the authors based on Olgyay (1998) and Aelenei et al. (2016).

Since the proposed artifact is a built facade and its objective is to optimize climate performance, knowing the local climate to the proposed intervention is imperative, as it provides the main inputs not only to be used as design constraints, but also to inform a climate diagnosis that should outline the problems to be solved by the artifact's design.

Olgyay (1998) proposes a framework for bioclimatic oriented design which was mentioned in Figure 1. Aelenei et al. (2016) and Bernal et al. (2020) also propose envelope design frameworks. Overall, they all depend on a clear apprehension of goals, constraints and inputs for a design to be proposed and then validated.

The following applications were selected as the toolset for problem analysis and design process in response to the nature of the problems to be addressed, software accessibility, interoperability and prior expertise: Rhinoceros (a CAD modeling software), Grasshopper (embedded into Rhinoceros, it allows parametric modeling through a visual programming interface, providing a bridge for data-driven design where input values are parameters to be operated upon); Archicad (BIM platform that interoperates with Rhinoceros and Grasshopper), Ladybug Tools (computer application that can be used as a Grasshopper plugin for environmental analyses), Radiance (lighting simulation tool that dialogues with Ladybug Tools), @it (Grasshopper plugin GIS data visualization).

3 Proposed approach and implementation

3.1 Diagnosis: context analysis and adaptability gaps

Before choosing a study object for this research, it is essential to recover the idea behind comfort and how this concept permeates architecture. It is also important to place the climate conditions and the context particularities that should guide the design of buildings in Fortaleza, Brazil.

The intention of an architecture concerned with bioclimatic comfort is trying to guarantee users the maintenance of the ideal comfort conditions necessary for use and permanence, through cooling, heating and natural lighting as passive thermal conditioning strategies (Olgyay, 1998).

Comfort exists, then, as the result of a perception bound to individual notions, particular experiences and punctual variations (Monteiro et al., 2015) – the aim of bioclimatic architecture is to find the balance between these three factors. Here, the importance of knowing the climate is understood, with its typical values and its environmental variables, and the role of design guidelines, architectural elements and construction technologies becomes clear, aimed at promoting the reduction of energy consumption and comfort optimization (Lamberts et al., 2014).

The first step was to understand the bioclimatic conditions of Fortaleza and how they relate to architectural features that impact thermal performance. The ideal passive thermal conditioning strategy for the local climate is *permanent cross ventilation,* and Lamberts et al. (2014) remark that *shading* is a fundamental strategy in most Brazilian cities, which must be applied when temperatures exceed 20ºC.

The selected existing building holds common characteristics of educational typologies, and an initial analysis of its current condition was developed to locate key intervention demands. In the building scale, we noticed that (1) the building's implantation had one of the longest facades facing west; (2) recessed platbands, not associated with any other shading mechanism, do not protect the facades at certain times of the year; (3) the manufactured brise-soleil do not match the designers' intention expressed in the model and have a reduced efficiency; (5) there is a lack of landscaping and tree planting, an efficient and sustainable solution to create pleasant, shady areas; and it is highlighted, in time, that (6) the compromise of the facades with the installation of air conditioning condensers indicates that use and occupation conditions would be supported by a high investment in artificial-only air conditioning (and its associated costs).

The main variable chosen to be addressed in this initial application study was *solar radiation,* but visibility and access to daylight were also considered. This selection acknowledged some limits brought by the post-construction character of the proposed intervention, as well as time constraints related to the undergraduate course assignment.

3.2 Data collection and preparation

The analysis process began with the development of a synthesized model of the building, which prioritizes only the essential attributes for incident radiation analysis, such as volumetry and the positioning of openings (Figure 2). The model was updated based on the confrontation of recent photographic records and the available BIM model, to minimize discrepancies in relation to the actual state of the building, which could affect the results of the analyses.

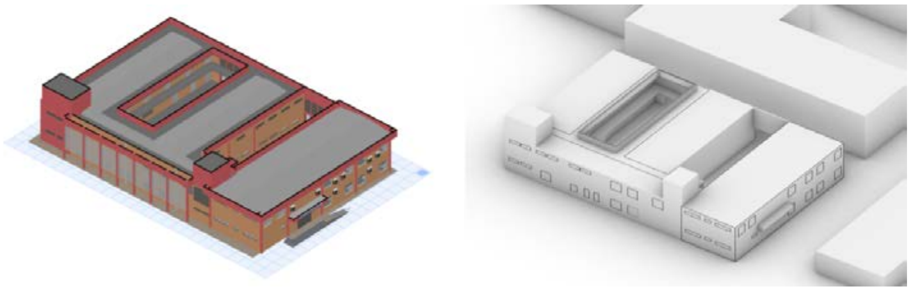

Figure 2. Original BIM model and simplified model of the building. Source: Elaborated by the authors using the BIM model provided by the Office of Integrated Engineering Projects (EPE-DIATEC-UFC).

After that, we have modeled the building's surroundings, using a georeferenced dataset provided by the local government containing geometry and data related to the city's individual buildings. A vicinity radius was established to make sure that the selected constructions would influence the simulation results due to immediate proximity and the consequent obstruction of direct sunlight radiation, while reducing the incidence of irrelevant data weighting the processing runs.

To convert primitive geometries and data in the surrounding model, a script capable of accessing and translating geospatial data was utilized within the Rhinoceros + Grasshopper ecosystem (Robert McNeel & Associates, 2021) – with the toolset offered by the plugin @it (Ertugrul & Nowrouzi, 2016), we have used the height feature available in the dataset provided as an extrusion factor, generating a volumetric, simplified, and georeferenced model of the radius of interest.

Using the climate analysis tools available through the Ladybug Tools (Ladybug Tools LCC, 2021) collection, a series of simulations was developed, based on a TMY (Typical Meteorological Years) weather data file made available by the National Institute of Meteorology (INMET, 2018), to assess how the building under study performs in its bioclimatic context.

3.3 Analysis results

The radiation study was executed considering an annual analysis period and the result is the average incident radiation on the surface of the geometries. The results show that, on an annual basis, the west and north facades are more susceptible to heat and should be better protected – the color differences in Figure 3 indicate the impacts of a simple shading device, as shown in an eye comparison between a protected and a non-protected portion of the west facade. The high incidence of heat on external walls and roof points to the necessity of both light and somehow reflective solutions for the envelope.

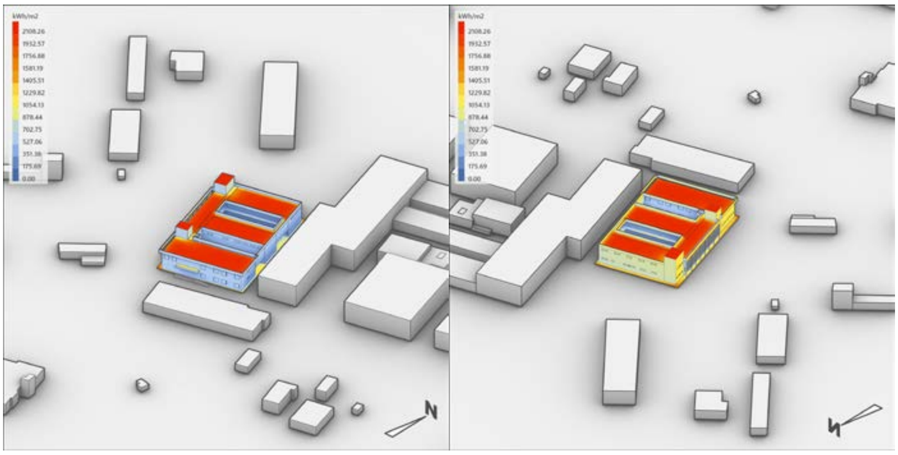

Figure 3. Average annual solar radiation on the building's envelope. Source: Authors.

It is necessary to mention that the reflections of solar energy from the ground and surroundings were not considered in the analysis performed, due to limitations of the tool chosen for the simulation. However, despite this impact on accuracy, we consider this approximation sufficient for the purpose of the study, as it assesses the impact of most solar radiation on the building envelope, allowing us to assume its negative effects on bioclimatic comfort despite possible influences other than direct and diffuse radiation.

3.4 Data-driven parameters

The main challenge to be faced involved developing a solution that would address the need for balancing shading and natural lighting, without overprotecting and blocking the views, nor opening too much for solar radiation. This goal was pursued using modularity as a basic principle, as the ease of documentation, manufacturing and assembly could easily be assimilated by available technology and local labor.

The first idea that came into play was to reduce the complexity of the solution – designing vertical planes to cover the facades analyzed. In these planes, we have proposed a fixed grid composed of cells which were assigned a remapped numeric value from 0 to 1, based on a categorization and further normalization of the values outputted by the radiation simulation. With a reparametrized representation of this simulation, where each segment was assigned a specific color from a predefined gradient, – from blue, for less radiation incidence, to red, indicating more – it was possible to assess and modify each individual facade without losing the integrity of the envelope.

The sizing of these segments followed logistical and financial feasibility criteria, considering the budgetary limitations for technology and skilled labor in the construction and assembly of these parts, which guided the proposal to a scale that could be worked with the available resources.

As a strategy for variation and for visual clearance and light permeability, the grid cells closest to openings were mapped, as shown in Figure 4 as the clear panels, and assessed as a new category, for which specific typologies of modules, more open, would be assigned. This solution has also proved to be advantageous for creating formal variation in surfaces where solar radiation uniformly falls along its entire length, as in the case of the west facade.

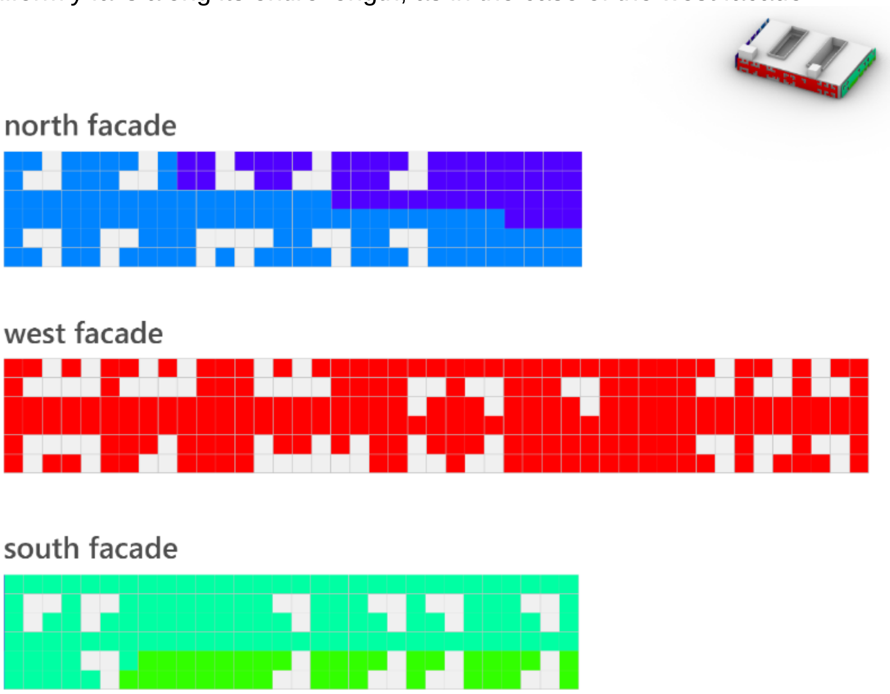

Figure 4. Facades recategorized by color based on the radiation values. Source: Authors.

By establishing permeability ranges based on the values retrieved from the radiation analyses, brick-based modules started to be suggested to test the limits of our solution. In addition to both financial and productive accessibility justifying this choice, the use of the brick also refers to the materiality of ceramics in the culture of Latin America construction heritage, since colonial times and still frequently seen in houses and settlements as a constructive element.

Designed by associating a common and affordable type of perforated ceramic block in a standard frame (to be detailed in future studies), module families were proposed based on two main criteria: *permeability*, varying the number of existing blocks within a single module; and *formal disposition*, related to the organization of the blocks within the module itself. Figure 5 shows the variation spectrum.

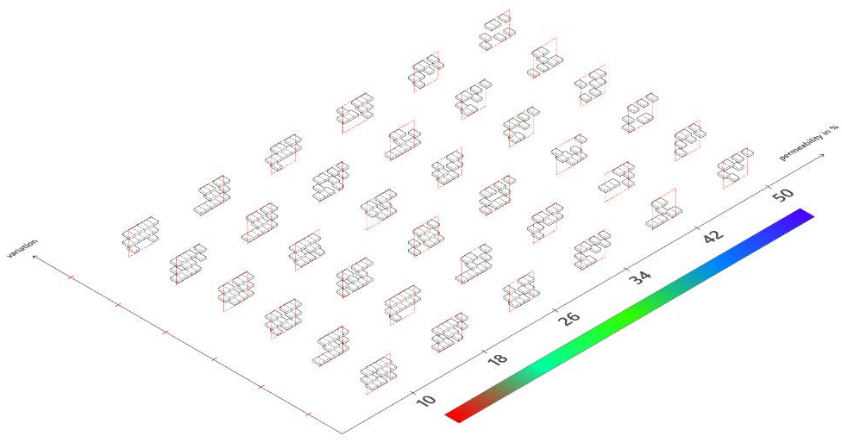

Figure 5. Modular brick solution varying by permeability (right to left) and formal disposition (up to down). Source: Authors.

The algorithm can generate a series of iterations, which can vary according to the objectives and priorities established by the architects (Figure 6). Parameters such as cost, complexity, aesthetics, available tooling and a range of other issues can directly or indirectly influence the design approach and consequently, the chosen module pattern.

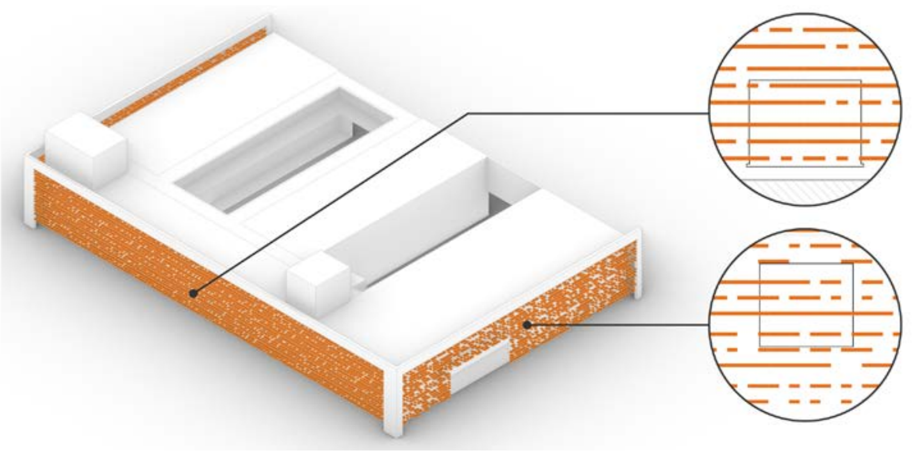

Figure 6. Iteration study, highlighting the pattern's permeability on different facades. Source: Authors.

However, despite the option chosen within the scope of iterations, the variations share the ability to absorb a significant fraction of the solar radiation incident on the external walls, behaving not only as an effective and cheap shading solution, but as a distinct second skin that uses the characteristics of the original building and its surroundings as formal inputs (Figure 7).

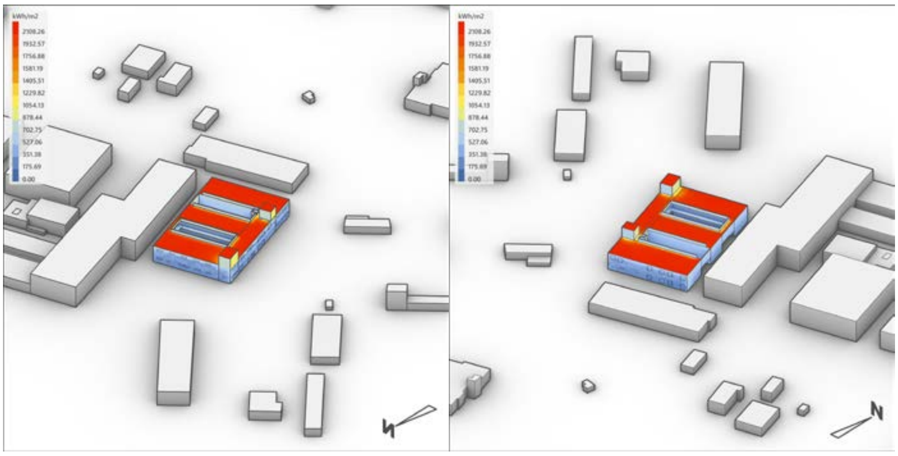

Figure 7. Average annual solar radiation on the building's envelope after the second skin proposal. The second skin was hidden to show its impact on the existing facade. Source: Authors.

4 Discussion

The concept of sustainability rests on three pillars: environmental, social and economic. Each of them may have a different weight according to the local context, the needs and the availability of a network of people and processes. In the field of architecture, providing environmental quality to existing buildings has been an increasingly important concern, even when premises of environmental comfort and performance have not been initially considered. The best solutions will not always relate to market trends – design intelligence can aid to combine design and manufacturing technologies to locally established making and knowledge.

The core aspect of the proposed artifact matches one of the main mass customization features: modularity. It associates variety with some degree of standardization, which can be adjusted according to the desired permeability, as well as local manufacturing conditions and workforce, including, for instance, the use of existing, ordinary construction elements like bricks or standardized panels. Additionally, the number of variables can be reduced for lowering costs. In this case, the use of modularity also enhances flexibility, as the customization process embeds different combinations of simple components, which can be replaced or removed over time if necessary.

This work presented the first iteration cycle in a DSR framework, which comprised a schematic facade composition. Future work may comprise a deeper level of information, concerning materiality, as well as artisanal and digital construction issues, which relates to the artifact's production phase. Embracing the study of the relationship between design and execution, subsequent phases can address the role of interoperability in translating the final solution, initially proposed in a CAD tool, to a BIM platform.

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