Parametric approach using the Wave Function Collapse algorithm integrated with Building Information Modeling to create volumetric studies

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Abstract. This research presents the development of a design approach for residential spaces in hybrid buildings using Wave Function Collapse (WFC) algorithms. The proposal seeks to challenge housing standardization in urban centers, anchored on principles of general systems theory, modularity, flexibility and information modeling. After a literature review, an algorithm was developed integrating Archicad, Rhinoceros and Grasshopper platforms using the Monoceros WFC plug-in. A volumetric model of a hybrid building was instantiated in the city of Fortaleza, Brazil, following adjacency rules and constraints based on local urban codes. The algorithm was capable of interpreting and slicing the terrain to accommodate occupancy and permeability areas; generating a point grid from the geometry; simulating spatial organizations through WFC; and translating the resulting geometric plans into BIM compliant floor and wall elements. The study contributes with a technological framework to overcome typological rigidity in housing developments during early-stage design.

Keywords: Wave function collapse, Parametric architecture, Modular buildings, Flexible housing, Generative algorithm.

1 Introduction

Housing first emerged as a basic survival need. Serving as an interface, protection, and refuge against harsh weather and predators, it has evolved over time into a space for social, cultural, and familial interaction. In contemporary society, housing has come to be recognized as a fundamental human right, constitutionally guaranteed in many nations (UN-Habitat, 2014). However, housing has also become a product subject to the laws of supply and demand in the real estate

market. This dual nature, as both a human right and a consumer good, places housing at the center of urgent debates, particularly in the context of rapid urbanization and growing socio-spatial inequalities.

According to Habraken (1999), the idea of housing as a commodity stems from its mass production, which is based on maximizing efficiency and delivering a finished product. This approach fails to consider inhabitants' actual demands, preferences, and expressions. The author argues that strengthening the bond between people and their homes depends on the ability to change them over time according to evolving needs. This can be achieved through careful design of supports.

Habraken's (1999) approach can be related to the concept of linkage, which allows the emergence of collective forms in dynamic architectural and urban systems (Maki & Goldberg, 1964). This physical and functional connection provides cohesion between different elements. In Vieira's (2008) systemic view, cohesion involves establishing a balanced number of relationships, that is, a structure that is neither minimal nor excessive, but which allows for a certain degree of flexibility, thus enabling the system to remain in place over time.

In urban centers, contemporary and sustainable housing goes beyond the limits of dwelling units. Leite and Awad (2012) argue that the mixture of activities in compact territories contributes to urban vitality, public safety, as well as social, environmental, and economic efficiency of infrastructures. Hybrid buildings create this diversity at the block's microscale: they blend multiple uses, between public and private; they confront the modernist form-function rule, and they provide permeability with the urban environment (Mozas, 2014). In Latin America, residential use is emphasized as an inseparable core of hybrid buildings (Cunha et al., 2019).

Transitioning between the scale of the housing unit and that of the block is one of the challenges in designing a hybrid building, when guided by principles of linkage, flexibility and cohesion, which requires openness to different ways of living and geometric results. As Maki and Goldberg (1964, p. 28) state, "[t]he aesthetics of the collective form necessitates new definitions of scale and proportion of buildings". Modularity helps to articulate distinct dimensions, enhancing the legibility of spaces (Hertzberger, 2001). Added to this is the provision of polyvalent spaces, open to the interpretation and identity of each inhabitant (Hertzberger, 2001). Frameworks such as supports theory (Habraken, 1999), or frame and generic space (Leupen, 2006), focus on providing fixed elements that multiply possibilities of use, based on their dimensioning, positioning and articulation with polyvalent spaces.

Computational thinking has been consistently applied in the generation of housing alternatives, with technologies such as parametric design (Kolarevic, 2003) and building information modeling (BIM) (Eastman et al., 2011). When designing hybrid buildings, it enables the integration of multiple variables, expanding the experimentation and visualization of scenarios that question the current logic of housing production.

Inspired by its quantum mechanics homonymous, Wave Function Collapse (WFC) generates complex spatial patterns from simple rules. WFC operates through “observation-propagation”: it begins with a “possibility field” (all viable configurations) and iteratively collapses options until arriving at a coherent solution that respects adjacency constraints, symmetry requirements, and contextual relationships (Gumin, 2016). This methodology is suitable for design situations requiring large-scale adaptability, including urban planning, modular architecture, and digital landscape generation, avoiding spatial monotony while providing variation within repetition. It is also useful in resource-constrained contexts or rapid-response scenarios, such as emergency housing or informal settlement upgrading.

Monoceros is a plug-in created at studio Subdigital (Pernecký & Tóth, 2021) to operationalize the WFC framework in Rhinoceros/Grasshopper (Robert McNeel & Associates, 2025), which enables architects to define elemental modules (e.g., housing blocks, circulation paths, green areas) and their connective rules within a grid. For instance, a residential unit might require street access, while a park module must adjoin low-density zones. The algorithm autonomously propagates these elements according to initial rules, gradually generating configurations for filling the entire grid boundary (Pernecký & Tóth, 2021).

As both a design tool and spatial reimagining method, WFC demonstrates capacity to translate apparent chaos into functional order. As multiple competing constraints must be resolved, carefully defining a rule set is an essential yet demanding task in the search for an accurate solution (Pernecký & Tóth, 2021). The algorithm's probabilistic nature accommodates non-linear design thinking, positioning it as an advancement in parametric design methodologies and dialoguing with other generative techniques (Gumin, 2016; Oxman, 2006).

Using these tools, this study aims to develop a design approach for residential spaces in hybrid buildings by exploring methods of spatial organization through Wave Function Collapse (WFC) algorithms. The proposal applies modularity as a design and future flexibility resource, in a workflow that integrates BIM and parametric modeling through the Monoceros WFC plug-in during early-stage design. An application study is conducted in the city of Fortaleza, Ceará, Brazil, utilizing a parametric point grid that conforms to local legislation and urban parameters.

2 Methodology

This study is based on the conception of architecture as an interdependent organizational system, anchored in the Systems Ontology (Vieira, 2008). Within this paradigm, architectural components function as autonomous yet interconnected elements through symbolic relationships, sharing properties among form, function, and construction. This logic enables the representation of architecture as a complex entity of dynamic interactions, where components transform into flexible signs, which were adapted in this research to relational

contexts with the WFC algorithm to simulate organic occupations. The abstraction of architectural models into modular blocks achieves a balance between computational efficiency and the simulation of occupancy complexity (Müller et al., 2023).

The method involved the development of a framework with three interoperable algorithmic modules. The WFC algorithm was instantiated in the Manuel Dias Branco neighborhood in Fortaleza, Brazil, to propose a hybrid building that seeks to engage with alternative forms of housing densification in the local urban context.

2.1 Algorithm development

The research method integrated parametric modeling, combining WFC, BIM, and 3D modeling, to generate preliminary volumetrics compliant with urban regulations. The framework, which is illustrated in Figure 1, has progressed along the following steps: (1) Interpreted urban parameters (buildable limits, permeability); (2) generated a volumetric study with the Monoceros WFC plug-in (Pernecký & Tóth, 2021) aligned with programmatic requirements; and (3) translated parent geometries into BIM elements. The modules were developed in Rhinoceros/Grasshopper (Robert McNeel & Associates, 2025), to process site-specific constraints into viable volumetric proposals, and subsequently transposed to Archicad's BIM environment (Graphisoft, 2024).

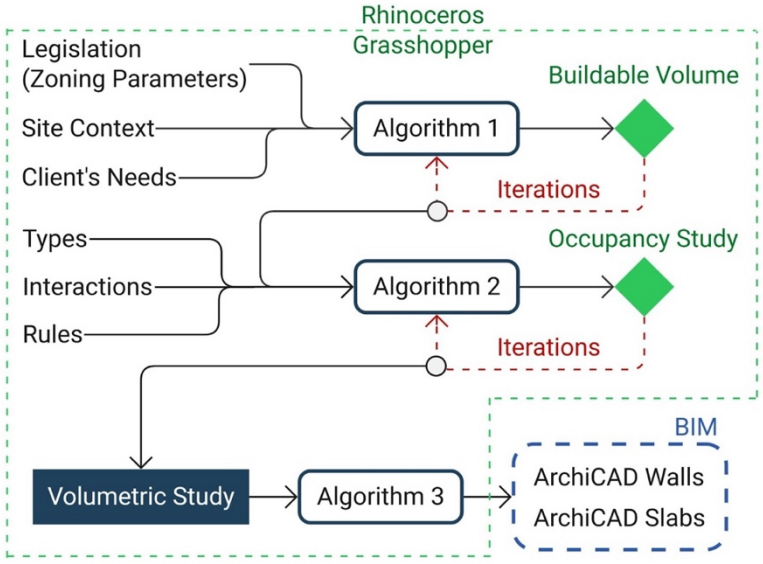

Figure 1. Workflow diagram. Source: authors.

Algorithm 1 mapped urban constraints, using native Grasshopper tools to create a working grid, filtered the grid area following the imposed zoning restrictions,

removed parts of the grid that would be considered permeable areas and non-buildable areas, and finally extruded the remaining grid blocks to create the envelope for the occupancy areas. The extruded geometry was then subdivided into a point grid (Figure 2), based on the centroid of each uniform grid size, allowing us to import this data directly into the Monoceros WFC plug-in.

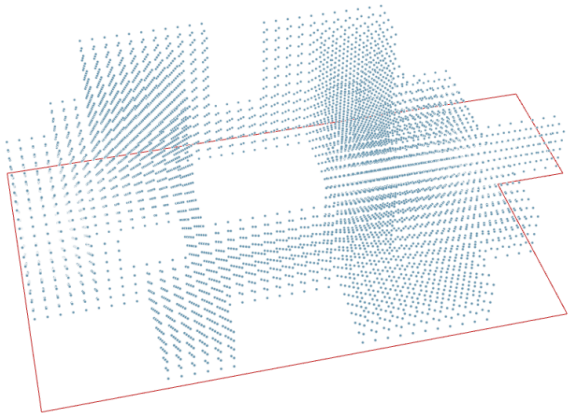

Figure 2. Random point grid generated from Algorithm 1. Source: authors.

Algorithm 2 integrated typologies and combinatorial rules via Monoceros, using the previous point grid data to feed the slot requirement in the plug-in, as it represents the tridimensional space where the algorithm simulates the interactions between the modules and rules provided.

Algorithm 3 converted outputs into BIM elements, in Archicad, through a simple geometry normal analysis and filtering, providing us with the reference line needed to construct walls and reference planes to construct slabs in Archicad.

2.2 Application study: Fortaleza, Brazil

In this research, the city of Fortaleza, located in northeastern Brazil, was selected for instantiating a building developed with the WFC algorithm. In 2022, Fortaleza recorded 2.4 million inhabitants, which placed it as 4th in the country in terms of population (IBGE, 2022). The vertical housing development in this city intensified from the 1950s onwards (Cavalcante, 2015), and nowadays multi-family dwellings are distributed throughout the territory.

This kind of building presents specific characteristics in Fortaleza, which can be related to local urban codes and vary according to where they are located. In regions with higher income and land value, building density has often been associated with vertical buildings: laminar typologies which are distanced from the site boundaries proportionally to their height (Cavalcante, 2015). Social housing developments (e.g. Minha Casa Minha Vida program), in turn, have been built in

the south of the city, applying models based on a mass production logic (Nascimento, 2018).

However, in the history of multi-family and mixed-use buildings in Fortaleza, some examples have challenged local market standards, such as Panorama Artesanal, from 1975, designed by architects Delberg Ponce de Leon and Fauso Nilo, which was defined as a hybrid development during an interview to Cavalcante (2015). Panorama Artesanal has recently undergone adaptive reuse and currently hosts a gastronomy and hotel management school. Another example is the São Pedro building, opened in 1951 and unfortunately demolished in 2024 (Figure 3). This building mixed residential, hotel and commercial uses in three block fronts, varying plans across different floors (Cavalcante, 2015).

Figure 3. São Pedro building, photographed in 2015. Source: authors.

In this application study, the WFC algorithm was instanced in the Manuel Dias Branco neighborhood, in a block bordering the Cidade 2000 neighborhood. Cidade 2000's urban design contrasts with its surroundings: the blocks are rectangular-shaped, narrow but up to 350m long, and the lots are distributed longitudinally, facing two different streets (Costa, 1988). The hybrid building designed during the present research proposed a dialogue with alternative ways of densifying housing in the city of Fortaleza, establishing a connection with Cidade 2000's urban form.

3 Results

Firstly, the urban parameter interpreter (Algorithm 1, Figure 4) automated zoning code application through manual textual inputs (setbacks, permeability ratios, floor

area ratios, maximum height) and terrain geometry processing. Terrain data of the selected block in Fortaleza was imported from Archicad as BREP surfaces, with edges manually categorized by setback typologies. Boolean operations enforced the fundamental constraint: Total Area − Permeable Area ≤ Maximum Buildable Area, yielding a compliant 2D envelope subsequently extruded to regulatory height limits, generating legally conforming massing studies.

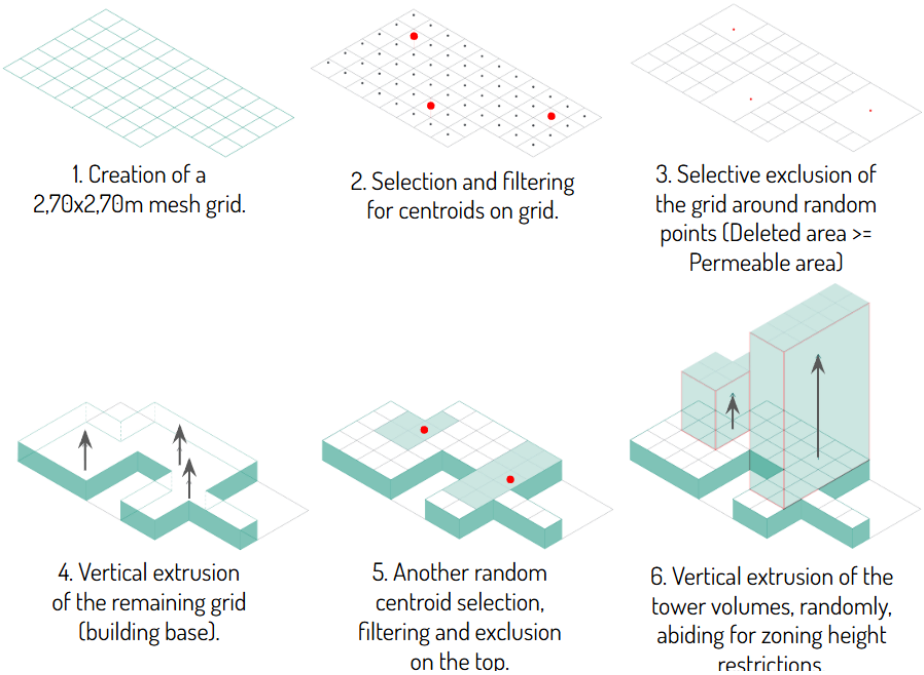

Figure 4. Explanatory diagram of Algorithm 1. Source: authors.

For optimizing WFC processing in Monoceros, architectural typologies underwent radical modular abstraction. Programmatic requirements were processed into 2.70m x 2.70m z 2.70m cuboids, with minimum aggregations of three modules (≈20m²) per dwelling unit. This simplification operationalized support structure flexibility principles (Habraken, 1999) while enabling complex organic configurations (Müller et al., 2023). Combinatorial rules governing adjacencies and functional hierarchies ensured spatial coherence.

The core volumetric simulator applied Monoceros WFC to resolve superpositions into viable spatial arrangements. Point grids that had been derived from regulatory envelopes populated orthogonal 3D grids, while modular components and topological constraints generated configurations connecting urban codes, programmatic needs, and constructive logic (Figure 5).

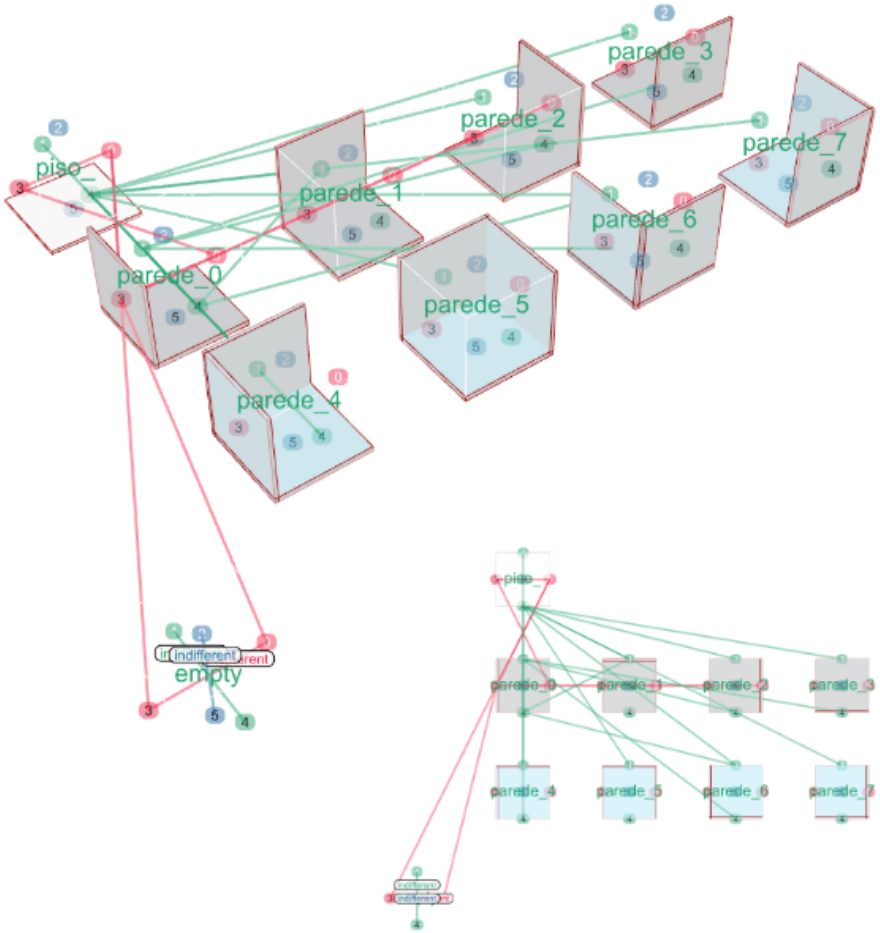

Figure 5. Final layout of modules and rules representing small groups of walls and slabs. Source: authors.

The WFC-to-BIM translation algorithm employed geometric filtering to separate horizontal surfaces (Z-normal vectors to floors) from vertical planes (X/Y-normal vectors to walls) Duplicate faces were eliminated via overlap detection before reference extraction, allowing the identification of wall base edges (lowest Z-value boundaries) and floor contours (horizontal surface boundaries). These elements were instantiated into BIM components through Archicad's Live Connection plug-in for Grasshopper, with materiality and thickness parameters predefined within the translation workflow (Figure 6).

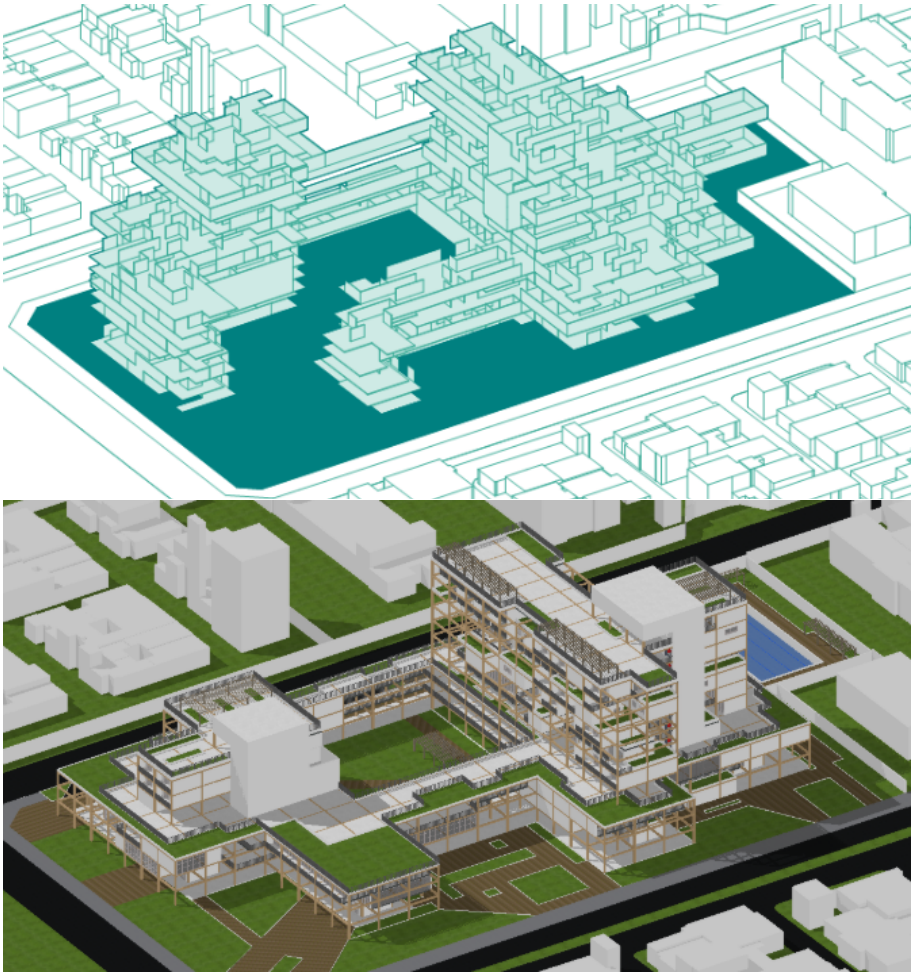

Figure 6. Volumetric study created by Monoceros, before undergoing manual adjustments (above), and final design proposal for the hybrid building in Archicad (below). Source: authors.

Resulting preliminary geometries intentionally excluded secondary elements (fenestration, finishes) to prioritize basic spatial logic. This simplified output reinforced technology's role as a design mediator rather than an autonomous agent (Negroponte, 1995), enabling iterative refinement while demonstrating viable WFC-BIM integration for regulatory-compliant design exploration.

4 Discussion

The integration of parametric methodologies in architectural practice presents a challenge to conventional design procedures. This paradigm shift demands not only technical proficiency but also a change in creative workflows. As geometry becomes dynamically responsive through algorithmic control, parametric tools transform linear design processes by reframing revisions, iterations, and conceptual restarts (Kolarevic, 2003). Parametric systems do not replace human intuition; rather, they amplify designers' capacity to explore solutions (Oxman, 2006). By integrating social, environmental, and economic variables into computational simulations, parametric workflows support the generation of more precise outcomes within compressed timeframes.

Applied to the Cidade 2000 neighborhood in Fortaleza-CE, Brazil, the framework demonstrated potential to overcome typological rigidity in housing policies (e.g., Brazilian public social housing projects like Minha Casa Minha Vida). By generating adaptive variations, it helped to integrate urban codes, local identity, and programmatic demands, optimizing preliminary stages and reducing rework. Thus, it offered an alternative to mass production, reaffirming housing as a fundamental right through responsive technological innovation.

Furthermore, the possibility of adaptation with existing programming algorithms in the field of gaming design, such as the case of Monoceros WFC, illustrates a different, more dynamic approach to the creation and proposal of such design frameworks, as it was shown in the resulting building. It imposed a different way of approaching and looking at architecture holistically.

This study was an initial analysis of the possibilities in using Wave Function Collapse algorithms in architecture, and how it could lead to solve an early design problem as the attendance to the zoning regulations. Much of the findings were collected in a short span of time, but regardless, the results attest the potential of this framework.

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