Parametric evaluation of urban compactness in Brazil: a computational study in Juiz de Fora

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Abstract. This paper presents an application of parametric techniques and tools to assess urban compactness in the city of Juiz de Fora, Brazil. A literature review identifies the objective metrics' role in urban design and how they are associated with the urban compactness paradigm. The case study provided results that characterize aspects of the built urban density and the mix of uses in the samples, exploring how parametric resources can help urban design. This research shed some light on how metrics can assist parametric urban design allowing performance measurement in the early design stages. It also highlights potentials, future studies, and challenges, establishing discussions about developing this field of knowledge in Brazil and even in Latin America.

Keywords: Urban Design, Parametric Urban Design, Computer-aided Urban Design, CityMetrics, Architectural Design

1 Introduction

Parametric tools have improved designers' work since their introduction in architectural tasks, with algorithmic languages reaching urban design from many perspectives (Kotnik, 2010; Leach, 2009a; Schumacher, 2009). This technique gained prominence for its architectural applications, with limited use in urbanism. Some authors argue that most parametric urban design methods have only the appearance of morphology and lack a deep understanding of the principles of urban structure formation (Çalışkan, 2017; Leach, 2009b; Yuhan, Zhenying & Yulong, 2020).

The often-used idea of complexity to study the evolution of urban components and create models based on the emergence of several shapes and structures is recurrently used by designers (Schumacher, 2009). On the other hand, this basic overlay of factors neither proves nor explains the nature of the interactions among urban elements (Leach, 2009b).

Some researchers highlight a need for new techniques that address the urban space supplying a demand for sustainability, innovation, and dynamic management, considering the context of urban population growth and the impact caused by cities on our planet. The environmental conditions of public spaces and buildings shape how people use external and internal spaces in their routines, and urban design is crucial to reverse this scenario, restoring the balance of the built environment so that it sustains more quality of life (Amorim, 2015; Bereitschaft & Debbage, 2013; Chokhachian *et al*., 2020; Farr, 2007).

Characterizing and evaluating urban areas in the initial design stages is essential to promote evidence-based / performance-based urban design actions. This paper identifies a possibility in which new tools/techniques can be inserted to increase efficiency and streamline management activities and urban design, justifying this research and outlining its objectives. We intend to contribute to the Computer-aided Architectural Design (CAAD) field, presenting a fruitful application of a parametric model to assess urban compactness indicators and establishing discussions about developing this field of knowledge in Brazil.

2 Methodology

This research applies the inductive method, outlining itself as applied research with a quali-quantitative approach with two and three-dimensional surveys of the urban form in three study areas. This approach consists of two main techniques: parametric modeling and algorithmic logic, and the methodological procedures were distributed in two steps within the workflow. In the first stage, a literature review identifies the metrics' role in urban design and how they are associated with the urban compactness paradigm. The review also identifies tools, parameters, and objective indicators that could be incorporated into the case study. The second stage corresponds to the parametric evaluation implementation in the study's samples. The evaluation sought to objectively characterize aspects of the built-up urban density and the diversity of uses. The *Rhinoceros3D* software and its generative plugin, *Grasshopper,* were adopted as our primary digital tool.

We selected three urban fabric samples from three neighborhoods to compose this research case study. We used components from the *CityMetrics* toolbox (Lima, 2017, Lima *et al*., 2017), chosen to assist in carrying out a parametric analysis of the *Mixed-use Index* (Hoek, 2008) and the Berghauser Pont & Haupt (2010) *Spacematrix* indicators. Then, a second scenario was structured based on the Hillier & Hanson (1984) *Social Logic of Space* theory, analyzing the axial axes' influence in each sample and addressing how they relate to the other metrics evaluated in the first scenario.

For the modeling stage and the following objective evaluation, the procedures performed were, in short:

a) definition of the three samples used in the research;
b) data harvest and treatment of files;
c) implementation of *CityMetrics* (inputs) to evaluate the indicators identified in the bibliographic review stage;
d) list the results obtained (outputs).

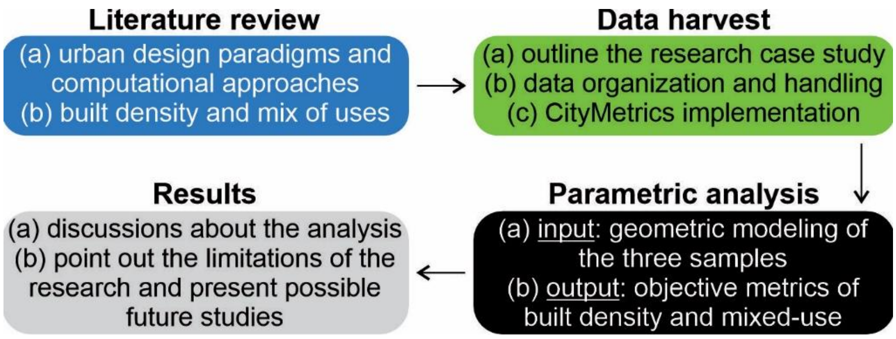

Figure 1. Summary of methodological procedures. Source: Authors, 2022.

2.1 *CityMetrics* - parametric toolbox for analysis and optimization of urban configurations

CityMetrics (Lima, 2017; Lima *et al.*, 2017) is a set of tools that articulates *Grasshopper3D* components associating metrics for performance evaluation based on algorithmic-parametric logic. The purpose of the toolbox is to assist in analysis and urban planning tasks, even enabling optimizations in different aspects related to the degree of efficiency and the possibilities of operation of geometric and algebraic configurations of an urban area. According to his developer, the model was designed to evaluate and optimize the performance of urban settings through metrics related to measurable principles derived from the *Transit-oriented Development* (TOD) paradigm, using the logic of the *Visual Programming Language* (VPL) to build *Generative Systems*. Among all the components available in the toolbox, only two were used in the case study reported by this research: the one for calculating the *Mixed-use Index* (MXI) and the one for calculating the indicators of built density *Spacematrix*.

2.2 The *Mixed-use Index* (MXI) and the *Spacematrix* indicators

Hoek (2008) developed the *Mixed-use Index* (MXI) to establish a relationship between the total residential and non-residential built areas in a given sample. The MXI approaches the total sum of the entire area in all buildings, including all floors above ground level (street level). The index aims to verify the balance of uses in the sample. Hoek (2008) states that when the ratio between the residential and non-residential areas approaches the balance, the urban diversity is close to the ideal. Consequently, the greater the diversity of uses in the area.

Berghauser Pont & Haupt (2010) presented a set of indicators that characterize some of the essential aspects of built density. We evaluated three fundamental indicators proposed by the authors: (i) total land covered by buildings (*Ground Space Index* - GSI; (ii) vertical use in areas where the soil is occupied (*Floor Space Index* - FSI) and (iii) density of the street network (*Network Density* – N). The GSI represents a relationship between the sample and the projections of buildings on the ground. It can be obtained through a ratio between the total area and the sum of the building's soil areas. The FSI represents how much the projections of buildings in the sample are used, which can be obtained by dividing the total constructed area (also considering the vertical floors) and the sample area. The network density N is defined as the length of the network per square meter of base area (m/m2) and is calculated as the sum of the entire network of internal roads and half the length of the network of external roads (perimeter of the sample).

3 Urban compactness and the role of parametric tools in designing sustainable neighborhoods: a short review

Rogers (1998) pointed out that the survival of a society depends on the balance between population, natural resources, and the environment. One of the problems addressed in his work Cities for a Small Planet is the current pattern of urban development and how cities compromise environmental balance, destroying ecosystems and threatening human survival on a planet whose natural resources are finite. Farr (2007) identified that in this context of global urbanization, soil, water, and energy scarcity concerns sustainability. Amorim (2015) understood that these new concerns were allied to a demand for new services, the expansion of consumption patterns, the incorporation of parts of the populations that were previously not served or were marginalized, the fight against pollution and climate change, and the environment protection. These new demands also significantly increase economic and financial costs to enable a series of essential services to face these challenges.

Hoek (2008) stated that social changes are one of the most relevant forces that drive urban transformation and development, as well as the definition of urban design characteristics. In the 20th century, the economy shifted from industrial production and distribution to knowledge-based services and creation. The rapid development in modern times of economy and technology has increased the scale of operation from a local to a global scale. In contrast, Ascher (2005) highlights that contemporary urbanization processes are determined by de-industrialization and the reinvention of the concept of modernity, de-traditionalizing the typical industrial society. Hoek (2008) states that these processes accompany a reassessment of urban uses, aiming to stimulate diversity and, consequently, an ideal scenario to promote urbanity, economic development, and consumption of products.

It is important to reinforce that the high urban density paradigm assumes that its benefits can only be fully viable through an adequate infrastructure, or as Chakrabarti (2014) defines, the infrastructure of opportunity: schools, cultural centers, hospitals, health centers, parks, and other fundamental social facilities that enable social aspirations such as employment, education, leisure, and health. In summary: urban compactness contributes to sustainability by bringing the houses closer to the work buildings and leisure areas, in a logic where the car becomes expendable, given that the distances between spaces become accessible by walking (Farr, 2007, Frey 2003, Lima, 2017, Rogers, 1998, Talen, 2011).

Rauws, Moroni & Cozollino (2020) identified that the main reason for the ineffectiveness of some current urban design actions is that they aim, in most cases, to order the growth of cities and control all the agents that interact there through prescriptive actions. Rauws & De Roo (2016) highlighted that cities spontaneously develop a capacity for adaptation — identified by the authors as the capacity for self-organization — which produces, in parallel, a challenging scenario for orthodox urban design actions.

The definition of parametric design, as presented by Woodbury (2010) and Jabi (2013), presents it as a design process based on algorithmic thinking in order to allow the expression of well-defined parameters and rules that, together, determine, encode and establish a relationship between the proposal and the project response. Beirão *et al*. (2010) understand that within the field of urban planning, the paradigm of computational tools meant a possibility to quickly visualize the impact of changes in the panorama of the shape of the city — such as aspects of density or diversity.

Through parametric design, it is possible to manipulate and adjust parameters such as soil utilization, the ratio between heights, and the percentage of open space, among other aspects. This technique would allow managers to make decisions based on a database related to different scenarios, aiming at incorporating an infinity of variables into a cohesive system and evaluating the dynamic effects of different parameters on each other and the shape of cities. Thus, it is possible to state that using parametric tools in urban design is a growing and relevant technique. This technique should be understood as an aid to processes in which it is possible to insert objective metrics in the initial stages of design, allowing fast production, visualization, modification, and evaluation of possible solutions.

4 The case study and the results

As criteria for selecting research samples, three neighborhoods were chosen in the city of Juiz de Fora (Brazil): São Pedro (Sample 1), Benfica

(Sample 2), and Centro (Sample 3). The three neighborhoods are located in the most populous regions of the city. They are of great importance for the structure of the city's urban fabric, playing a central role in both economic and historical aspects. Through empirical perception, the three samples also presented a recent scenario of intense morphological transformations, arousing our interest in objectively evaluating them. Three sections of the urban fabric were established and spontaneously defined based on the selection of blocks in the most central part of each sample: in the São Pedro neighborhood, the blocks adjacent to Avenida Presidente Costa e Silva were selected; in the Benfica sample, the blocks adjacent to Rua Martins Barbosa were selected; and in the Centro sample, the blocks that make up the region popularly known as the "expanded central triangle" were selected. Figure 2 illustrates the 3D modeling of the three samples evaluated.

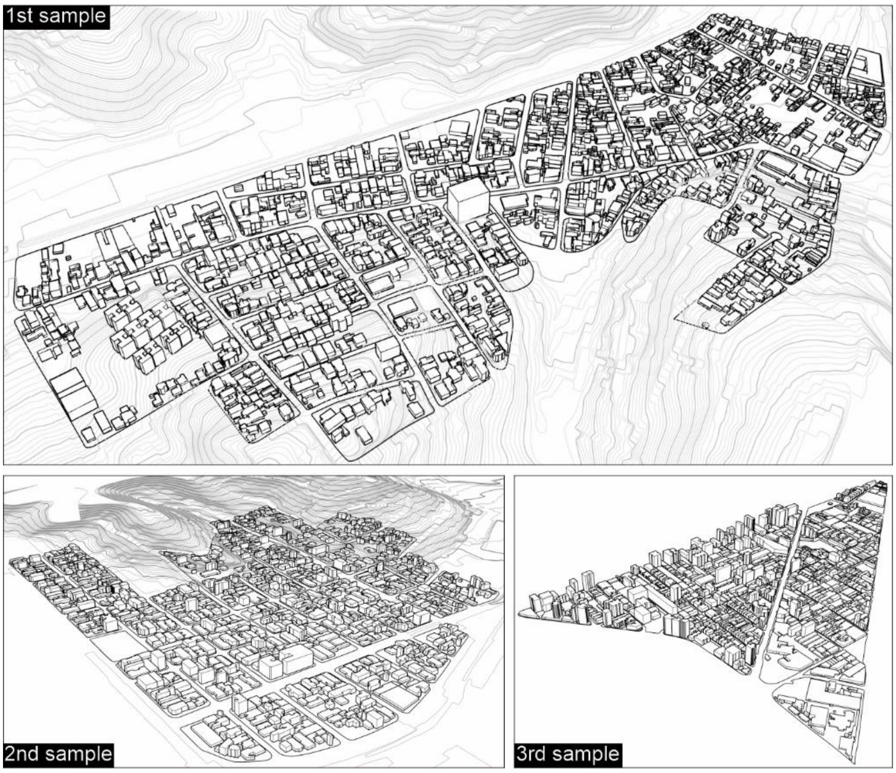

Figure 2. 3D modeling of the samples inside *Rhinoceros3D*. Source: Authors, 2022**.**

The objective metrics related to the aspects evaluated (built density and mix of uses) were collected from the modeling stage, evaluating the three samples in two different scenarios. Regarding the mix of uses in the samples in the first scenario, Samples 1 and 2 present an excessively monofunctional panorama (greater residential use), with a low supply of services/non-residential uses; Sample 3 has a slight imbalance. Figure 3 illustrates the uses in the three evaluated areas, and Figure 5 presents the results objectively in a graphic. The metric characterization of the built density is presented in Table 1.

Figure 3. Map of buildings uses of the three samples. In yellow, residential use; orange, non-residential use; light red, mixed-use. No scale. Source: Authors, 2022.

After the first analysis, we organized a new scenario (Scenario 2) to evaluate how the sample's main street impacts urban compacity metrics. In Scenario 2, verifying the uniformity of the urban configuration in the three samples was also possible. A significant variation in the values of the indicators addressed means that the uniformity of the urban configuration is low, pointing out that the morphological characteristics of the main street differ drastically from the rest of the sample. Figure 3 illustrates Scenario 2, identifying uses and buildings not considered in the objective assessment. Figure 5 can also be used to query the MXI graphic results. The second part of Table 1 presents the metric characterization of the built density in both scenarios, allowing a comparison of the results.

Figure 4. Maps identifying the disregarded buildings in scenario 2 (in black). In yellow, residential use; orange, non-residential use; light red, mixed-use. No scale. Source: Authors, 2022.

In Sample 1, the results varied considerably concerning MXI and built density (GSI and FSI), which suggests that the neighborhood concentrates the highest services and buildings on its main street. In Sample 2, the slight drop in the indicators points to a significant presence of services on the main street, keeping part of the non-residential uses distributed in the rest of the sample. The buildings on the main street of this clipping had a reasonable impact on the GSI and FSI indicators, suggesting that in the central portion of the sample, the buildings occupy more land and have a higher utilization coefficient. Sample 3 had a uniform drop in the MXI, GSI, and FSI indicators values, remaining close to those obtained in Scenario 1, indicating a very uniform distribution of uses and the pattern of occupation and land use.

Table 1: Results of the objective evaluation in both scenarios.

Scenario 01	*Mixed-use Index* (%)		*Spacematrix* indicators		
	Res	non-Res	GSI	FSI	N
Sample 1	84	16	0.33	0.68	0.015
Sample 2	77	23	0.40	0.81	0.018
Sample 3	42	58	0.62	2.04	0.016
Scenario 02	*Mixed-use Index* (%)		*Spacematrix* indicators		
	Res	non-Res	GSI	FSI	N
Sample 1	95	5	0.27	0.38	N/A
Sample 2	83	17	0.35	0.65	
Sample 3	47	53	0.57	1.8	

Source: Authors, 2022.

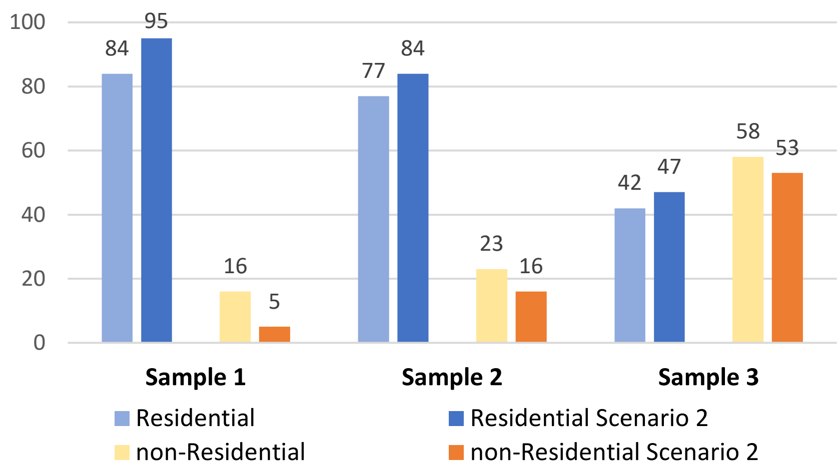

Figure 5. Illustration of the MXI variation in both scenarios. Source: Authors, 2022.

Regarding the built density (Table 1), in Scenario 1, the evaluation showed that Sample 2 has a higher land occupation than in Sample 1 and is smaller than in Sample 3. The values found for the GSI indicator indicate that samples 1 and 2 can still increase total land use within the maximum legislated potential (GSI = 0.60). In Sample 3, the value of this indicator is already a little above the ideal. Regarding the floor area ratio, the FSI result showed that the three samples have low average use of the soil, especially in samples 1 and 2. Regarding the street network density (N), the result was positive for the sample from the Benfica neighborhood (Sample 2), which has the highest network density. The region proved well-served by streets and suggested a good scenario for walkability/adoption of alternative transport. The São Pedro neighborhood sample (Sample 1) has the lowest network density among the three samples, which can be explained by the presence of dispersed and large blocks in its urban fabric. The sample from the Centro neighborhood (Sample 3) presents an average network density among all the three samples evaluated by this research.

In Scenario 2, the mix of use (MXI) and built density (GSI and FSI) indicators of Sample 1 varied a lot, revealing that the neighborhood concentrates the services and buildings of greater size and occupation of the land in front of Avenida Presidente Costa e Silva. Sample 2 showed a slight drop in the indicators, pointing to a large concentration of services on the main street, but still maintaining a good distribution in the rest of the sample. The buildings on the main road of this clipping had a reasonable impact on the GSI and FSI indicators, suggesting that along the central street axis, the buildings occupy more land and have a higher utilization coefficient. Sample 3 had a uniform drop in the MXI, GSI, and FSI indicators, which remained close to those obtained in Scenario 1. This result means that the mix of uses is uniform in this segment and the pattern of use and land occupation. This indicator (N) was not evaluated in Scenario 2 since no changes were proposed in the configuration of the streets.

5 Discussions

Evaluating the urban space is a task that deals with tangible and intangible aspects: as Christopher Alexander has taught us, the city does not have the structural simplicity of a tree. Although it is hard to measure sensations such as insecurity, well-being, or happiness among people who inhabit cities, it is known that these sensations can be associated with specific and measurable characteristics of the urban space. As presented in the short review, compact cities optimize public transport and encourage alternative transportation, reducing the impact caused by cars and even supporting a healthier life. From the social perspective, compactness allows the inhabitants to create a relationship of intimacy with the urban space, increasing the flow of people and the possibilities of meeting and coexistence between them. It also creates more opportunities for social development and a more significant stimulus for establishing small businesses: an impulse for several exchanges that encompass social, human, and financial capital.

This research highlights the relevance of metric approaches to investigating cities at different scales: the evaluation allowed a quick visualization that the most effective use of the soil is related to regions with the most diversity of uses in the three samples, which promotes more urbanity. We shed some light on how parametric evaluation can support the urban design and how quality indicators can be converted into metrics that enable objective analysis and more efficient design proposals within a specific scope. The adoption of urban metrics must be understood as an essential aspect of more sustainable urban planning because they allow performance measurement in the early design stages, providing a quick evaluation even in simple experiments, as in the case study presented in this paper.

Thus, this paper intends to stimulate the use of computational resources as the primary technique to deal with information modeling tasks and the physical characterization of cities, associated with approaches that can evaluate urban performance through objective indexes and metrics. Characterizing the aspects of built urban density and the mix of uses is an essential step towards designing more sustainable neighborhoods and cities, favoring the development of urban spaces with balanced social dynamics.

This article also emphasizes the importance of carrying out specific studies on performance metrics contextualized with Brazil's social reality, impacting the development of an identity for Brazilian parametric urban design, highlighting the cultural aspects of cities, and supporting the design of a better urban space. Looking ahead, one possibility that seems to us to be very fruitful is using parametric techniques to articulate metrics that can guide urban densification based on the potential for urban transformation, aiming for more sustainable and socially balanced cities.

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