Sea level rise and real estate market impacts on urban development in a ca/agent-based model

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ABSTRACT
This study presents a proposal for a hybrid model (based on agents and cellular automata) which aims to analyse the long-term effects of sea level rise and real estate market dynamics on the urban development of coastal cities in Rio Grande do Sul, a state located in south Brazil. The model's operation is based on the Complexity Theory of Cities and seeks to simulate the study area’s urban growth by replicating the process of spatial allocation of residential and commercial activities and the variations in built form and territorial attributes - such as land value and attractiveness - that result from this process. To accomplish this, specific modules were developed to determine the land value of each part of the territory through the behaviour of individual agents and to compute land attractiveness metrics through the representation of the cellular automaton as a graph. The proposed model is tested in an experiment for Tramandaí and Imbé - two coastal municipalities in Rio Grande do Sul - considering different scenarios of building restrictions and sea level rise. The results show: i) the model's ability to contribute to the development of planning policies for the study area; ii) indications of its consistency in relation to theoretical statements; and iii) its limitations in reproducing the dynamics that generate diffuse urban growth patterns.

Keywords: Urban Modelling, Cellular Automata, Agent-Based Modelling, Urban Planning, Complexity Theory of Cities.

RESUMO
Este estudo apresenta uma proposta de modelo híbrido (baseado em agentes e autômatos celulares) que visa analisar os efeitos de longo prazo do aumento do nível do mar e das dinâmicas do mercado imobiliário no desenvolvimento urbano de cidades do litoral do Rio Grande do Sul. A operação do modelo é baseada na Teoria da Complexidade aplicada...
às cidades e busca simular o crescimento urbano da área de estudo replicando o processo de alocação espacial de atividades residenciais e comerciais, bem como as variações da forma construída e de atributos territoriais - como valor e atratividade do solo - que resultam desse processo. Para tanto, foram desenvolvidos módulos específicos para determinar o valor do solo de cada parte do território por meio do comportamento individual dos agentes urbanos e para calcular métricas de atratividade das frações do território por meio da representação do autômato celular como um grafo. O modelo proposto é testado em um experimento para Tramandaí e Imbé - dois municípios conurbados do litoral norte gaúcho - considerando diferentes cenários de legislação urbanística e elevação do nível do mar. Os resultados mostram: i) a capacidade do modelo em contribuir para o desenvolvimento de políticas de planejamento para a área de estudo; ii) indícios de sua consistência em relação a enunciados teóricos; e iii) suas limitações em reproduzir as dinâmicas que resultam em um crescimento urbano difuso.

**Palavras-Chave:** Modelagem Urbana, Autômatos Celulares, Modelagem Baseada em Agentes, Planejamento Urbano, Teoria da Complexidade Aplicada às Cidades.

**1 INTRODUCTION**

The coastal cities of Rio Grande do Sul, a state located in south Brazil, present demographic and environmental dynamics that may significantly impact its urban configuration, natural environment and quality of urban life in the near future. First of all, the region has presented the highest population growth rates of Rio Grande do Sul in the last two decades (RIO GRANDE DO SUL, 2015) and its number of inhabitants increases up to 250% during summer months due to the touristic attractiveness of local beaches (ZUANAZZI; BARTELS, 2016). These aspects create challenges for urban management and also contribute to the existence of an intense local real estate market based on the sale of holiday houses and on short-term rentals for tourists (KLUGE, 2015), which creates pressure in favour of the growth of urban areas over the natural environment. The main effect of this urban growth is the suppression of vegetation and dunes, making cities more susceptible to natural disasters (RIO GRANDE DO SUL, 2015), such as storms, floods or even the sea level rise due to climate change that are expected to impact the coast of Rio Grande do Sul before the end of the century (CLIMATE CENTRAL, 2020).

In the literature, no studies of these issues were found for this specific region, even though modelling and simulation methods have been recurrently applied for other regions of the world to investigate possible future changes in urban areas (CASALI; HEINIMANN, 2019; KIM; NEWMAN, 2020; TABERNA et al., 2020). In order to contribute with this set of studies by adapting existing modelling and simulation methods to a specific empirical context, this research aims to analyse future development scenarios...
of coastal municipalities in Rio Grande do Sul using cellular automata and agents. More specifically, the study intends to simulate the spatial distribution of residential and commercial activities, as well as land value dynamics, based primarily on the modelling of: i) the locational preferences of the different population groups that inhabit the study area; ii) the economic relations that affect the local real estate market; and iii) the impacts of sea level rise on the urban environment. Such analysis is expected to anticipate relevant urban trends resulting from the dynamics of the study area.

This paper presents the model that was developed to simulate the behaviour of the study area and also an experiment for the municipalities of Tramandaí and Imbé – located in the coast of Rio Grande do Sul - considering different scenarios of building restrictions and sea level rise. The results of such experiment prove the model's ability to contribute to the development of planning policies for the study area, especially those regarding building restrictions, and also show its limitations in reproducing the dynamics that generate diffuse urban growth patterns.

2 RESEARCH BACKGROUND

Complex systems are systems whose components are other complex systems and whose functioning presents the emergence of decentralized processes that influence its global behaviour (BATTY, 2007a). Cities are complex systems, because they consist of numerous individuals with complex behaviour that interact locally with each other and with the surrounding environment, influencing the general shape of the city (BATTY, 2007b). Besides, cities are also self-organizing systems, since their components don’t exclusively react to top-down ruling, but also generate endogenous and emergent forms of organization (PORTUGALI, 2016).

Because the city is a complex self-organizing system, its functioning presents characteristic dynamics of these systems: emergency, far-from-equilibrium functioning, non-linearity, path dependence and robustness (BATTY, 2007a). Therefore, in order to model cities as self-organizing complex systems, it is necessary to treat them as processes, incorporating time in the model and assuming an algorithmic approach in which the model is executed iteratively step by step (WHITE; ENGELEN; ULJEE, 2015). For the implementation of this approach, two specific models stand out: Cellular Automata (CA) and Multi-Agent Models (MAM).

CA consists of the subdivision of the territory into cells (BATTY, 2007a) that present: i) a state, which assumes a value from a predefined list of possibilities; ii) a set
of transition rules that indicate how the state change over time; and iii) other internal attributes that can be used in the definition of the transition rules (TORRENS, 2000; WHITE; ENGELEN; ULJEE, 2015). The states and attributes generally provide a geographical description of the territory - land cover, use, population density - and the transition rules tend to incorporate spatial or economic statements referring to city dynamics (TORRENS, 2003).

MAMs distinguish themselves from CAs because their constituent agents can move within the model. Each agent also has its own state, attributes and transition rules (BATTY, 2007b). However, due to their mobility, they do not have an immutable neighbourhood (TORRENS, 2003), hence interactions between agents generally happen either between those who become close enough during simulation or those connected by remote means of communication (CROOKS; PATEL; WISE, 2014; DAHAL; CHOW, 2014). Agents can also interact with the territory through the use of CAs and MAMs in a hybrid model, which also enables the territory - usually represented by the CA – to be modified according to the interaction with the agents and to modify these agents (TORRENS, 2003).

3 METHODOLOGY

This study aims to develop a model that will support the analysis of urban development scenarios for coastal municipalities of Rio Grande do Sul considering their specific population and environmental dynamics. To this end, the analysed municipalities are considered to be complex systems, their form being the result of the emergence of the local actions of their inhabitants and their interaction with the territory and the existing planning rules. Because of the use of this approach, MAMs and CAs become the most appropriate options to represent the dynamics of the study area of this study. In this section, the elements that constitute such proposed model are described.

3.1 STUDY AREA

This study aims to analyse the north coast of Rio Grande do Sul due to its specific demographic and environmental dynamics that may impact the local urban configuration in the coming decades. The first of these dynamics is the significant seasonal variation of the region’s population, which is approximately 3.5 times higher during summer months due to the tourism of the local beaches (ZUANAZZI; BARTELS, 2016), resulting in the overuse of urban infrastructure during summer and its underuse in the winter. Also, the
region has shown the highest demographic growth of Rio Grande do Sul in the last two decades, in contrast to the population decrease observed in the rest of the state (RIO GRANDE DO SUL, 2015). Such dynamics generate an intense real estate market - based mainly in the acquisition of buildings to be used as vacation residence and in short term rents for summer tourists (KLUGE, 2015) – that presses for the flexibilization of planning and building rules in order to accommodate more inhabitants and tourists, consequently requiring higher investments in public infrastructure.

Another issue is the increase of sea level caused by climate change. Estimates by Kulp and Strauss (2019) - illustrated by Climate Central (2020) - indicate that parts of the north coast of Rio Grande do Sul may be below sea level by the end of this century. This phenomenon has the potential to cause: i) the spatial redistribution of the population that inhabits the areas at risk of flooding; ii) the necessity to build water containment infrastructure; and iii) the decrease of land value in the areas at risk of flooding.

Among the coastal municipalities of Rio Grande do Sul, Imbé and Tramandaí (Figure 1a) - two conurbated municipalities - were chosen as the study area because of their importance for the region in demographic and economic terms. In addition, the area is the most threatened by an eventual sea rise in Rio Grande do Sul (Figure 1b). It is understood, therefore, that the application of modelling and simulation techniques can be useful to anticipate possible effects of such phenomena on the region’s urban configuration, enabling more efficient urban planning policies for all coastal municipalities of Rio Grande do Sul.

Figure 1. (a) Location of the state of Rio Grande do Sul and of the municipalities of Imbé and Tramandaí; (b) Estimated sea level rise for Imbé and Tramandaí for the year 2080 (CLIMATE CENTRAL, 2020).
3.2 MODEL COMPONENTS

The model is composed by: i) agents that represent individuals with different incomes and locational preferences who settle in cities to perform residential or commercial activities\(^1\); ii) territorial fractions represented by the cells of a CA that incorporate the computation of evolving land values, building restrictions and locational privileges in order to represent the territorial dynamics that are generated by the agents’ behaviour; and iii) Real Estate Developers (REDs), which construct new building units in the most sought regions when it is observed the opportunity of profiting from this operation.

Figure 2 diagrammatically represents the simulation process considering the actions of the three described entities. Such process can be summarized as follows: i) the simulation begins with the creation of the CA from geospatial bases; ii) each cell has different attributes and such differentiation enables the computation of the shortest paths between cells, which are later used to update the attractiveness attributes of the CA throughout the simulation; iii) a random number of agents are added to the CA with random characteristics; iv) agents look for a cell to settle in and, in each of the following iterations, check if that cell still meets its requirements; when this ceases to occur, they search for another cell to settle in; v) during this entire process, the cells constantly update their state and attributes according to its neighbours’ behaviour; vi) these changes induce REDs to analyse the territory and expand cells that may generate profit for them.

Figure 2. Functioning of the model.

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\(^{1}\) The selection of these two kinds of activities is due to the fact that the economy of the study area is predominantly based on commercial activities, with little participation from other land uses (RIO GRANDE DO SUL, 2015).
3.2.1 Cellular Automata (CA)

The cells of the CA represent hexagonal fractions of the territory whose edges measure approximately 75 meters in length. Since the general objective of the model is to represent the occupation intensity of the territory, it was defined that the state of the cells would represent the quantity of agents located in it. The computation of such state depends on a set of attributes which is common to all cells (Table 1) and represents the characteristics of the study area’s territory with relevant influence on its land occupation. These attributes are constantly updated during simulation as the cells interact with agents and REDs. Also, their value also influences the actions of these other two entities, as will be described in the following subsections. Such dynamics result in the constant variation of the cells’ state, which changes each time an agent settles in or leaves it.

Table 1. Description of the CA’s attributes

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urbanization Capacity</td>
<td>Describes whether buildings can be built in the cell to house agents.</td>
</tr>
<tr>
<td>Reachability</td>
<td>Indicates whether the cell may be part of the path of an agent between cells. It is used in the computation of the network analysis metrics that measure the cells’ attractiveness.</td>
</tr>
<tr>
<td>Capacity of Agents</td>
<td>Maximum number of agents that can settle in the cell. Reproduces the influence of the building restrictions established by local legislation.</td>
</tr>
<tr>
<td>Load</td>
<td>An estimate of the attractors existing in the cell, divided into natural load (such as beaches and vegetation areas) and urban load (active residences and commerce).</td>
</tr>
<tr>
<td>Spatial Opportunity</td>
<td>Measures the accessibility to commercial use and services from the point of view of residential demands as proposed by Krafta (1999).</td>
</tr>
<tr>
<td>Spatial Convergence</td>
<td>Measures the spatial privileges of the territory from the point of view of commerce and services as proposed by Krafta (1996).</td>
</tr>
<tr>
<td>Land Value</td>
<td>An estimate of the expected sale value of the cell.</td>
</tr>
</tbody>
</table>

An auxiliary layer was added to the CA in which the set of cells is represented as a graph: each cell’s centroid is a node connected to its reachable neighbours (Figure 3), following the nodal representation of urban systems as defined by Krafta (2014). This additional layer enables the use of network analysis measures - such as spatial opportunity and convergence (KRAFTA, 1996, 1999) - as attributes of the CA cells, which can be used in the exchange of information between non-adjacent cells.

Figure 3. Representation of the CA as a graph.

![Traditional CA Representation](image1) + ![Graph Representation](image2) = ![CA + Graph](image3)

Traditional CA Representation: Simulation of changes in cell’s state and attributes.
Graph Representation: Computation of network analysis metrics (spatial opportunity and convergence).
CA + Graph: Network analysis metrics can be used in the simulation of cell’s behaviour.
In such graph representation, the impedance of the connections – i.e., the cost for an agent to move from one cell to another - is defined according to the cell’s proximity to the main existing roads: connections between cells that intersect highways have a lower impedance value - because they allow greater flows - than connections that depend on lower hierarchical roads (Figure 4). This attribute affects the system’s behaviour because it affects the computation of spatial opportunity and convergence metrics, since they are based on the shortest path (the one with the lowest sum of impedances) between each pair of reachable cells.

Figure 4. The impedances depend on the road with the highest hierarchy intersecting the cell.

The attractiveness of the cell – measured by the network analysis metrics - as well as its building restrictions, directly influence the cells’ land value. Filatova (2015) states that the prices of land properties depend not only on its physical and geographical characteristics, but also on the existing conditions of the market. Therefore, to better reproduce the dynamics of land value variation, it is required to somehow represent the level of interest of existing agents for each cell. To this end, the following process of land value estimation was proposed, loosely based on Filatova (2015): each time an occupied cell is evaluated as adequate by an agent, its land value is increased; on the other hand, if a cell does not receive any interest from an agent during an iteration, its land value decreases. This way, cells that constantly attract agents have increasing land values, while cells that do not generate interest see their value gradually decreasing.

3.2.2 Agents

Agents represent individuals who carry out residential and commercial activities in urban areas. Their individual behaviour is dictated by the attributes presented in Table 2, being Land Use the most influential one, since it defines, based on Krafta
(1996,1999), the kind of cell the agent will look for: residential agents seek the ones with higher values of spatial opportunity, while commercial agents seek cells with higher values of spatial convergence. As for the other attributes, Income and Required Attractiveness basically limit the set of possible cells where the agents may settle in, while the Maximum Occupation Time limits the time an agent may spend in a single cell.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Land Use</td>
<td>Indicates whether the agent represents a commercial or residential activity.</td>
</tr>
<tr>
<td>Income</td>
<td>Maximum land value of a cell that the agent can afford in order to settle in it.</td>
</tr>
<tr>
<td>Required Attractiveness</td>
<td>Minimum value of spatial opportunity (for residential agents) or spatial convergence (for commercial agents) that the agent requires in order to settle in a cell.</td>
</tr>
<tr>
<td>Maximum Occupation Time</td>
<td>An estimate of the attractors existing in the cell. Divided into natural load (such as beaches and vegetation areas) and urban load (active residences and commerce).</td>
</tr>
</tbody>
</table>

Simulation effectively starts when agents are initialized and start to interact with the CA. When initialized, each agent analyses the land value and attractiveness attributes of a set of randomly selected cells, being verified: i) whether the cell has a lower land value than the agent's income; ii) whether its attractiveness is greater than the agent's requirement; and iii) if it is the most attractive among analysed cells. If such a cell is found and it is not fully occupied, it will be defined as the agent’s current best option. If the cell is already occupied, the agent will discard it, but the value of that cell will increase in order to reflect the existing demand for it. At the end, the agent establishes itself in the best option it finds, increasing the cell’s urban load value. If no suitable location is found, the agent leaves the system. There are three conditions that cause the agent to leave a cell: i) if the cell's value becomes higher than the agent's income; ii) if the attractiveness becomes lower than the agent’s requirement; or iii) if the maximum occupation time is reached. When one of these situations occurs, the agent searches for another location following the previously described process.

3.2.3 Real Estate Developers (RED)

REDS increase the number of units in a cell - i.e., the number of agents that it can host - when they verify the possibility of profiting from this operation. At each iteration, the developer computes, for a random set of cells, the expected profit from the
construction and sale of new units according to the entrepreneur's equation (KRAFTA, 1994), as presented in Equation 1:

\[ L = (u * p) - (ct - cc), \] (1)

Where profit \( L \) is equal to expected earnings - average value of neighbouring cells \( p \) multiplied by the number of units \( u \) - subtracted by the cost of land purchase \( ct \) and the cost of construction \( cc \). The cells where the REDs expect to profit have their capacity expanded to the maximum allowed by local legislation.

REDs do not have a physical presence in the model, only the changes they make to the built form are visible. Therefore, they are represented by a computational function, meaning that, unlike what happens with agents and CA cells, the developer consists of a single homogeneous entity.

4 EXPERIMENT

The proposed model was tested in experiments for the municipalities of Tramandaí and Imbé, Brazil. Because the main objective was to make an initial analysis of the model, it was decided to start the simulations with the CA cells all unoccupied. Three different scenarios were considered: i) the entire territory could be occupied and all cells had the same building limits; ii) the occupation of the territory respected the buildings limits defined by current legislation; and iii) a situation similar to the previous one, but considering that in the hundredth iteration a set of areas at risk of flooding is defined and the agents inhabiting these cells must move to another cell.

The implementation of the model was executed on the Gama platform, which is a computational environment for the development of agent-based models and CAs (TAILLANDIER et al., 2019). The geospatial data that enabled the differentiation of the territory was obtained from the OpenStreetMap platform (IMBÉ RS, 2020), while the data of building limits was obtained from current legislation.

4.1 SCENARIO 1: SIMILAR BUILDING RESTRICTIONS

The first simulated scenario considered that all cells are capable of being urbanized and had the same building restrictions - up to five agents inhabiting each cell -

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2 The simulation of scenarios containing real data of population and built area is planned for the future stages of the research.
so its initial configuration is the one of Figure 6. Figure 7 shows that, because cells with positive load values were initially all located in the beach, its surroundings ended up concentrating most of the agents. This concentration gave rise to a positive feedback in which, due to having more agents, the attractiveness of the cells next to the beach increased, causing even more agents to move there. Figure 8 shows that the value of the cells near the beach become higher than the other parts of the territory due to the described concentration of agents. Also, the occupation of areas located far away from the beach intensifies after iteration 80 due to the depletion of cheap land by the sea and the consequent expulsion of lower income agents from there. Figure 9 and Figure 10 show that cells with higher convergence and opportunity values are located near the beach throughout the simulation.

Figure 6. Initial configuration for the simulation of the first scenario.

Figure 7. Number of agents and predominant use in cells during the simulation of the first scenario.
Figure 8. Land value during the simulation of the first scenario.

**Scenario 1**

- Land value

Figure 9. Spatial convergence of cells during the simulation of the first scenario.

**Scenario 1**

- Spatial convergence

Figure 10. Spatial opportunity of cells during the simulation of the first scenario.

**Scenario 1**

- Spatial opportunity
4.2 SCENARIO 2: BUILDING RESTRICTIONS ACCORDING TO CURRENT LEGISLATION

The second scenario used the rules of current urban legislation as reference for the definition of the cells’ capacity (Figure 11). In Figure 12, there is a greater concentration of agents in the so-called central area of Tramandaí where building restrictions are more permissible. As the occupation of this area intensifies, it seems to attract even more agents. Because the building restrictions allowed a higher number of agents than the previous simulation, there is no shortage of free spaces and, therefore, the occupation of the areas away from the beach is less intense.

In Figure 13, the lightest grey cells are those occupied by only one built unit, while the other shades of grey indicate cells whose capacity was increased by the action of REDs. Generally, the cells that were expanded by developers where the ones with more permissible building restrictions and with greater accessibility to main roads. Besides, the presence of buildings in an area accelerates the occupation of these same areas because it increases the urban load of its cells, making the appearance of new developments more likely there.

Figure 14 shows that more permissible building restrictions result in lower land values due to the lack of competition for the best locations. This phenomenon, in real life, would probably cause the increase of external individuals migrating to the region due to the lower prices. However, this is not currently being considered in the model, since the number of new agents in each iteration is, for now, the same for all iterations.

Figure 15 and Figure 16 reinforce the idea that the concentration of agents tends to reinforce itself and become increasingly more attractive. Such a process would probably end with the exhaustion of the area’s vacant cells, a factor that would cause the increase of land values and the appearance of new urban centres in remote locations.
Figure 12. Number of agents and predominant use in cells during the simulation of the second scenario.

Figure 13. Number of built units in the cells during the simulation of the second scenario.

Figure 14. Land value of cells during the simulation of the second scenario.
4.3 SCENARIO 3: FLOOD RISK SITUATION

The third scenario considers the effect of the risk of flooding due to sea level rise. The simulation started with a similar configuration to the previous scenario; however, after the 100th iteration, the cells belonging to the area at risk of flooding - according to the mapping of Climate Central (2020) for the year 2070 - cannot receive buildings and its agents must search for another cell to settle in. The behaviour of the system prior to the introduction of the flooding risk presented similar characteristics to those observed in the previous scenario, which is justified by the use of the same initial configurations.
Figure 17. Number of agents and predominant use in the third scenario considering risk of flooding.

Figure 18. Land value in the cells in the third scenario considering risk of flooding.

Figure 19. Spatial convergence in the third scenario considering risk of flooding.
The behaviour after the introduction of the risk of flooding is presented from Figure 17 to Figure 20. Figure 17 shows that, as the risk of flooding is considered, the occupation of the central area of Tramandaí intensifies, as well as in Imbé, next to one of its main roads. Figure 18 shows that the land value presents higher values, in relation to the previous scenario, in the central area of Tramandaí. Figure 19 and Figure 20 show an intensification of the concentration of the highest values of opportunity and convergence in a single focal point located in the central area of Tramandaí. These factors seem to be caused by the decrease in the number of available cells due to the risk of flooding, resulting in greater pressure on the remaining cells.

Figure 20. Spatial opportunity in cells in the third scenario considering risk of flooding.

5 DISCUSSION

The first scenario indicates a tendency for the population to spread evenly over the area along the beach, showing that, when we do not consider the differences between building limits, the locational privileges tend to be relatively homogenous in that area. The simulation of the second scenario, on the other hand, show a higher concentration of agents in a reduced area of Tramandaí due to the combination of more permissible building rules with better mobility and accessibility to commercial services. The attractiveness of this area tends to reinforce itself due to the agglomeration forces generated by such a combination of factors, a dynamic that becomes even more intense in the third scenario, in which, as the risk of flooding is inserted in the model, the concentration of agents in the border between Tramandaí and Imbé tends to be even more contrasting in relation to the number of agents inhabiting the rest of the territory.
From the point of view of planning policies, these results show that more permissible construction restrictions are effective in directing the population to certain areas. Therefore, because of the tendency of spatial concentrations to reinforce itself, it may be interesting for the municipalities to introduce more rigid building restrictions aiming at the creation of multiple development focuses, which was proved feasible by the simulation of the first scenario. Such planning policy seems even more appropriate when considering the effect of sea level rise: a more homogeneous distribution of population would offer more alternative places to receive individuals who inhabited the areas at risk of flooding, making less drastic the addition of required infrastructure in such areas.

As for the model's operating logic, despite the consistent reproduction of typical phenomena and dynamics of cities, the predominance of agglomeration forces in the simulations may be related to the absence of dynamics that would counterbalance their effects. Thus, it is possible that the insertion of the following items in the model may contribute to make it more accurate: a) the disadvantages generated by higher population densities, such as road congestion\(^3\). Considering this type of factor would result in remote areas having a higher attractiveness, enabling the reproduction of polycentric structures as is commonly observed in cities; b) the decrease in the attractiveness of buildings as they age, which would enable the representation of the cyclical substitution of buildings and the internal migration of agents it generates; and c) the incompatibility between certain types of agents, due to differences in use or income, which makes the proximity between certain agents unlikely, resulting in the homogenization of certain areas.

Another observation to be made is that the agents' behaviour seems robotic: they analyse a set of cells and always choose the most attractive one. One reason for this is that the model does not consider the arbitrariness that is inherent to human decisions, whose choices are not necessarily made based on the maximization of locational privileges, either because of personal motivation or due to bounded rationality. According to Batty (2007a), this arbitrariness can be represented with the addition of a degree of noise to the modelled decision-making process.

\(^3\) The increase in the impedance of paths located in the most populated areas was tested in order to take into account the effect of road congestion on the attractiveness of these areas. However, this proved to be computationally inefficient. It is expected, for future stages of the study, the use of some type of road performance metric in order to achieve the effect – such as those proposed Kureke and Bernardinis (2019).
6 FINAL REMARKS

The current work aimed to propose a predictive model of the urban configuration of the municipalities of Imbé and Tramandaí considering the locational preferences of its population groups, its intense real estate market dynamics and the impacts that the expected sea level rise may cause in the study area. The model was used to analyse future development scenarios of the north coast of Rio Grande do Sul in a set of experimental simulations that were executed considering three different development scenarios for the municipalities of Imbé and Tramandaí. The results seem to be coherent with the theoretical bases used to support the study and demonstrate the relevance of simulating the impacts of sea level rise and of the land market dynamics, since both interfered significantly in the urban configuration when they were introduced in the model. Besides, it is possible to draw conclusions about urban planning policies for the study area, especially regarding the definition of building restrictions, which, when permissible, contributed for the emergence of concentrations of agents in certain reduced areas, while, when more restrict, enable a more homogeneous urban growth. Considering the risk of flooding due to sea level rise, the concentration of agents in specific areas intensifies, indicating the necessity of encouraging the emergence of multiple urban centres in order to create multiple alternatives for those who eventually will be impacted by the flood.

The proposed model can still be further refined by, for example, using real population data as the simulation’s initial configuration or by making the area at risk of flooding grow gradually instead of directly appearing in its final form. Besides, additional methodological elements are planned to be included in the model, potentially changing the patterns observed in the results: i) the representation of the seasonality of land occupation, which would be achieved with the creation of agents that repeatedly inhabit the model for short periods of time; and ii) the insertion of long-term institutional equipment – such as parks, police stations, schools and hospitals – in the model’s initial configuration, which may affect the attractiveness of certain regions due to its location commonly being decided by top-down planning.

The described approach provided insights about the future of the study area, while still presenting the potential to provide more accurate results if specific complementary changes are performed. Therefore, it could become a relevant tool for urban modelling, justifying future studies aiming to develop this tool or to compare its performance with other predictive models proposed for different regions of the world.
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