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Theoretical study of the effect of ports in the formation of city systems

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Abstract

This paper explores theoretically the formation of a system of cities in which ports affect the spatial location and the size of cities. We use a complex systems and economic geography approach to generate 2D cellular automata to simulate the formation of the landscape of urban agglomerations based on different configurations of port locations. The dynamics of the model shows the emergence of the classical city-size distributions in which the number of ports and their layout affects the growth rate and location of the city-size values. Our findings showed that the two port-city configuration give rise to cities at a long distance from a small number of ports. The size of the cities shows a positive correlations with their distance to ports. A four port-city configuration showed that if the number of ports increases, lower city-sizes are attained and their population displays a negative correlations with their distance to ports. For a lateral configuration with a significantly increase in the number of ports, mainly homogeneous city-size distributions are favored with a slight long-distance size correlation. Therefore, our theoretical model shows a high internal consistency between the theory and assumptions used for describing reliable scenarios in the relationship of ports and urban systems.

Keywords: Ports, System of cities, Cellular automata, City-size distribution

Introduction

Ports are interrelated with cities in the development of urban systems since they connect discontinuous landscapes. It is generally accepted that port sites—artificial and natural harbors—affect the spatial location and organization of cities—agglomeration economies—by guiding the flow of resources based on transport, political, economical, or cultural attributes (Hoyle 1989; Lee et al. 2008; Hall and Jacobs 2012). Urban and transportation systems are interrelated to each other in which ports and cities are fundamental elements for representing nodes and understanding behaviors in such complex networks (Bird 1969, 1977, 1980; Notteboom et al. 2009). However, the empirical and theoretical evidence of the port and city relationship in describing their city-size or rank-size distributions remain unclear. Rank ordered distributions of urban contexts are commonly associated to the concept of universality as in complex systems, given that different urban systems show the same qualitative behavior, even though they differ in detail (Mart´ınez-Mekler et al. 2009; Bar-Yam 2016; Lugo et al. 2020). A recent study by Lugo et al., (2020) offers a recent empirical analysis about the role of ports in the dynamic of the city-size distribution. Based on a proximity analysis, they found that the city-size distribution is related to regions of influence in which port locations affect the city hierarchies. In particular, even though the spatial proximity of ports and cities differs in detail from regions and countries, the presence of the city-size distribution in a system of cities remains stable. Unfortunately, the mechanism of formation of a system of cities with such universality is not well understood. Therefore, based and motivated by the study of Lugo et. al., we undertake a complex systems approach based on the economic geography formulation to generate a theoretical model for describing the effect of ports into the emergence of a system of cities that shows skewed city-size distributions. The dynamics features are core elements of the model.

The economic geography outlook describes the presence of the city-size distribution based on spatial, general equilibrium formulations. In particular, Krugman (1996) shows an interaction model based on a simple linear network in which cities increase their size based on its past values and their neighbors. His findings showed that he dynamics of the growth of cities is strongly initial condition dependent, generating skewed statistical distributions in accordance with the observed rank-size distributions (Fujita et al. 1999a, 1999b). However, this formulation did not explicitly incorporate the port in the analysis as element for the emergence of such distributions. A novel step was provided by Fujita and Mori (1995), their work describes a first look of the port-city effect on urban areas. They describe the importance of port terminals to initiate the prosperity and development of cities. That is, the model describes the process by which port terminals became cities and how ports do not become cites because of the shadow effect. However, the emergence of a system of cities with their city-size distributions were not analyzed. Therefore, unlike these formulations, we propose an analysis of city systems under port conditions in which we put forward a generic, interaction model based on a 2D cellular automaton (2D CA). This generic model not only is consistent and extends the theoretical findings in Krugman (1996) and Fujita and Mori (1995), but also reproduces empirical patterns related to the relationship between ports and city locations (Lugo et al. 2020; Vance 1970).

Cellular automata have been successfully used in different physical and social analyses, in particular cities and urban areas (Toffoli and Margolus 1987; Wolfram 2002; Batty 2005). However, this type of computational model is not exclusive to applications concerning about urban areas that involve existing spatial structures. The relevance of using CAs is their capability to describe large-scale urban processes and not only understand real-world cases, but also to underly mechanisms related to common and differentiated statistical findings of the city-size distribution. Hence, in our interdisciplinary study, we address the following questions: How many cities will become port-city? Does the port location affect the growth of the city-size? Does the port location affect the spatial organization of the system of cities? Are port locations related to the emergence of skewed statistical distributions in city-size distributions? To answer these questions we compared Krugman's formulation with our model using an explorative data analysis. By means of a sensitivity analysis and model validation we found a set of parameters that generated the expected skewed values and showed the effect of them in the dynamics of the city-size growth. In particular, the 2D CA is based on an array that lies between periodic boundary grid configurations. These configurations describe connected and disconnected spaces related to the presence of water delimitations. We start with a closed boundary, and, subsequently, alter the grid by interconnecting some edge cells, i.e., we introduce the presence of maritime routes. Furthermore, the interaction of the majority of the cells is based on the Moore neighborhood, though some cells in the boundary present a modified version of neighbors connecting disjoint spaces. Therefore, each cell is associated with two attributes: city-size and port location. The former is of a quantitative nature while the latter is related to a qualitative feature.

From reference Lugo et al. (2020), we have reason to believe that increasing the number of port sites in the model should generate a system of cities characterized by common city-size distributions, in which the location of cities are randomly determined (see a schematic representation of this assumption in Fig. 1a). On the other hand, that decreasing number of port sites would generate a system of cities showing less skewed city-size distributions and displaying strategic locations of cities close to these transport nodes (see Fig. 1b). Therefore, port sites affect the spatial distribution of cities and their size. Our model provides clues based on generated data for an understanding of the relation between city-size distribution and port sites. The location of ports represents initial advantages of water-access. Some ports should develop as cities, while other cities start growing independently of ports. Based on simple transitional rules, our model shows the unification of different scenarios that describe the formation of a system of cities.

We divided the document into the following sections. The Literature Review shows theoretical and empirical references about the relationship between ports and cities in different contexts for understanding the formation of city-size distributions. The Materials section describes the cell attributes using in our model. The Methods section explains the 2D CA based on Krugman's formulation, and its implementation based on singular port configurations. It presents initial condition and the data analysis. The Results section shows our findings based on sensitivity analysis and model validation. We end with final remarks in a Discussion section followed by a Conclusion section.

Literature review

The literature of the relationship between ports and cities is abundant and diverse. According to our theoretical exercise, we identify two main areas of study. The first is the literature of theoretical approaches of studying cities and ports, and the second is

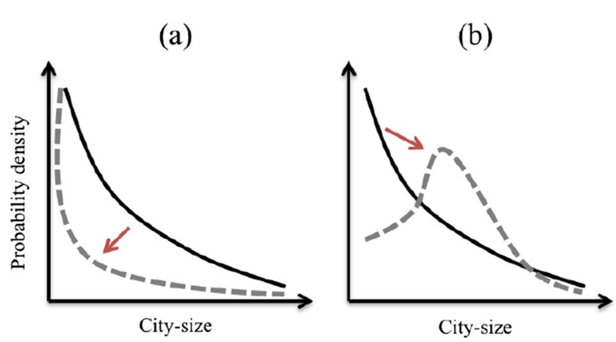

Fig. 1 Core assumptions. **a** Central-place. **b** Coastal-urban primacy. This figure exemplifies our assumptions about the behavior of the city-size distribution. The arrows in each subfigure point out the possible change in the city-size distribution. This figure was inspired by the ideas Vance (1970) and Lugo et al. (2020)

the empirical cases for understanding the structure and dynamics of portcity systems. Both areas have provided important insights, but their coordination to describe possible mechanisms behind the relationship between ports and cities has not been sufficient to obtain a clear picture. Therefore, for the purpose of simplicity, and recognizing the magnitude of the literature review, we only mention some of the significant studies related to our approach.

In the literature of theoretical approaches, we identify studies related to define the port-city. In particular, the work of Burghardt (1971), Bird (1977), and Brocard (1994) considered the port-city as a fundamental spatial node in the transportation network. The port city not only affects its surroundings, but also long-distance places. On the other hand, the work of Dogan (1988), Goss (1990), and Hoyle and Pinder (1992) indicated the strong interaction between the spatial and economic attributes of port-cities. Then, in the scale of a single port city, it showed different configurations of activities that are changed constantly depending on the time and context. Moreover, the work of Ducruet and Lee (2006) integrated different configurations of port-cities that could possibly explain past and current empirical findings. Finally, the seminal works of Fujita and Mori (1995) and Krugman (1996), which are generally considered fundamental studies in the New Economic Geography, have only had scarce scattered updates for including ports into the analysis and the use of a computer-based approaches. In particular, from 1990s to nowadays, we have only found decreasing number of studies in which a generic model for explaining the city-size distribution and the effect of port in the formation of cities is proposed. We consider those prominent studies as the last efforts for developing models from the economic geography that explain different and variable urban processes based on internal consistencies. Since the year 2000, there have been attempts to continue with those efforts, but the gap between the theory and empirical studies has increased. For example, the work of Mansori (2003), Venables (2005), and Cosar and Fagelbaum (2016) continued with the traditional approximation based on the general equilibrium formulation, meanwhile Ducruet et al. (2016, 2018) reinforced the line of empirical studies. On the other hand, the work of Batty (2005) and Pumain et al. (2009) showed similar efforts to those of the 90s, but these contributions came from different fields. In particular, they showed the importance of identifying the mechanisms of interaction between ports and cities to understand similar and diverse urban and transportation dynamics. Therefore, the port-city as a concept is constantly discussing, but it has been difficult to insert it in the theory of economic geography and to translate into different computational models.

In the literature of empirical cases, we have noticed an extraordinary increase in the number of urban studies with the lack of updated and renewed urban theories from the economic geography. However, these studies have showed and recorded important evidence on the existence of the city-size distribution in different countries and regions. In particular, we identify the work of Lugo et al. (2020), Notteboom et al. (2009), Lee et al. (2008), and Hall and Jacobs (2012) as different approximations to analyze the port-city formulation. These references suggest that each case shows particular attributes to define the port-city and its role in the transportation, geographic, and economic networks. A historical perspective about the relationship between ports and cities are the studies of Wiese (1981), Broeze (1989), Lawton and Lee (2002), and Lugo and

Alatriste-Contreras (2020). They suggested a strong relationship between ancient port sites or natural harbors and important settlements, which later developed as cities. Finally, particular cases for studying the port-city have showed the continued existence and development of the city in relation with ports, Chardonnet (1959), Socolow (1991), Marchand and Scott (1990), Wang and Olivier (2003). Even though, this literature has showed a large number of real-world cases related to existence of the city-size distribution in urban systems, it has only partially explained the underlying mechanisms. Therefore, the literature of empirical cases suggested that ports and cities have showed diverse and complex relationships that could be traced from ancient times and measured the level of their association.

In addition to the above literature references, it is important to mention published studies in which the empirical analysis is not the only way for validating a theoretical model. It is commonly misunderstood that real-world cases are the exclusive way of validating generic model. Based on the work of Sargent (1984), Rykiel (1996), Aumann (2007), Oberkampf and Roy (2010), and Kerr and Goathel (2014), model validation is a process relies on the operational and conceptual approximations together with a sensitivity analysis. The operational subprocess is related to the determination of whether or not the model output agrees with observed data. In our case, based on the extensive literature of empirical evidences of the city-size distribution, we aim to show that our model outputs agree with trends and qualitative data features. Next, the conceptual subprocess determines if the theory and assumptions underlying the model are justifiable. In this respect in our study we rely on the presence of internal consistencies between the theory, assumptions, initial conditions, and findings of different empirical cases. Finally, the sensitivity analysis provides essential data for determining the influence of parameters in the model outputs. Here, we implement a sensitivity analysis for exploring different values of parameters and identifying their influence in the formation of the city-size distribution. Therefore, we consider that our model indicates reliable outputs due to the process of model validation. Such a validation contributes to reduce the gap between the theoretical approaches and the empirical issues on the existence and emergence of the city-size distribution related to the interaction between ports and cities.

In next sections, we are going to present our theoretical analysis based on the CA approach. Our model attempts to show the interaction of ports and cities that describes the formation of the city-size distribution in urban contexts.

Materials

Because our study is a theoretical approximation to describe the emergence of a system of cities and its statistical distribution based on the city-size and portlocation, we describe the basic data to define these cell attributes. Such attributes are based on empirical studies that came from different formulations. The city-size is based on the economic geography, and the port-location is related to the maritime approach, which is more interdisciplinary than the former.

The city-size attribute is a value related to the number of inhabitants in a city. Most of the time, this value requires especial attention when defining a city in empirical studies due to the existence of different delimitations (Lugo et al. 2020; Gu´erin-Pace, F. 1995). For example, physical, social, or economic characteristics can delineate a city. There are other proxies related to it—i.e., the demand or economic mass—but they depend on scientific outlooks—i.e., economics or geography (Lugo et al. 2020). In these studies there is not a unique way to delimit a city. It depends on the goal of the analysis. However, in this study, we can identify a city related to a cell when its city-size value increases significantly. Each cell is geometrically the same, and it has the potential to develop as a city. The scale of the array matters to identify a cell as a city or a set of cell as cities. Therefore, we can add this attribute in our model without delimitation problems.

On the other hand, the port-location attribute is a qualitative value that identifies a set of cells in the boundary of the array. Because our array is set with a closed boundary, those cells with the port-location attribute describe the existence of ports and their connectivity. This connectivity is based on their neighborhood that performs as a single neighborhood (Fig. 2).

The Fig. 2 shows the case of two cells with the port-location attribute. The closed boundary of the array is changed to open in these particular cells since they share neighbors. However, there are different configurations to describe the portlocation effect to the formation of a system of cities (see the subsection of *The port configuration*). These configurations are in line with the work of Hoyle (1989) and Lee et al. (2008).

In addition, we used a set of Python libraries for modeling, computing and analyzing data. In particular, we used the third-party libraries https://matplotlib.org/ and https://numpy.org/. Therefore, we share the code related to the data, model, data analysis, and results. The code is available in the Open Science Framework (OSF) for transparency, openness, and reproducibility of science (Nosek et al. 2015), project: Modeling ports and city-systems.

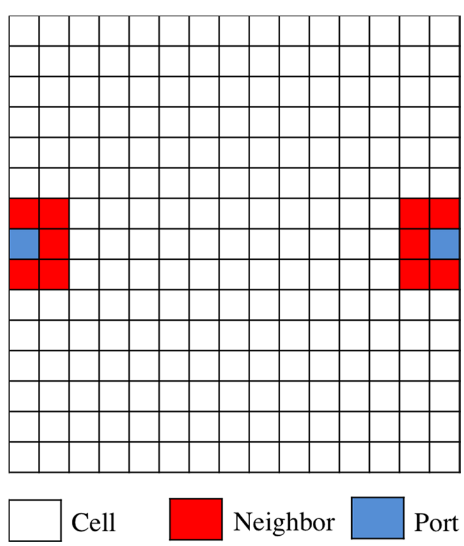

Fig. 2 Port-location attribute. The figure exemplifies the connectivity of two cells in a close boundary based on their neighbors. This figure was inspired by the model of Fujita and Mori (1995)

Methods

CAs are computational models formed by regular grid of cells—digital objects—with a finite number of states that depend on its neighbors, i.e., immediate vicinity. Such states are discrete and change in time and space by simple rules. These rules update the state of each cell as a function of its neighbors. Therefore, CAs produce global patterns based on local actions (Wolfram 2002). Here, we generate a 2D CA that used different grid configurations in which each cell shows the city-size and port attributes. Then, we applied an inferential data analysis based on a sensitivity analysis and model validation. The sensitivity analysis shows how different initial conditions affect the dynamics of the model, and the model validation compares these results with particular type of boundaries. In particular, cases without port configurations generate a system of cities characterized by the emergence of normal and skewed distributions. Therefore, we used the formulation of Krugman (1996) as our starting point, and we test it using different grid configurations related to port locations. Contrary to Fujita and Mori (1995), our model does not require the "shadow effect" restriction for replicating skewed city-size distributions. We focused on grid configurations with stable patterns that generate a system of cities with skewed distributions.

Krugman's formulation

The Krugman's formulation describes the interplay between centripetal and centrifugal forces that generates a system of cities characterized by skewed statistical distributions in their city-size growth (Krugman 1996; Fujita et al. 1999a). Following the notation in Batty (2005), we defined each cell that shows the attribute of city-size as $P_i(t)$, location i at time t. Taking into account the Moore neighborhood of each cell i, we define it as:

$$\overline{P}_i = \sum_{k \in \Omega} P_k(t)/9 \tag{1}$$

where k is the cell in the neighborhood Ω. Then P_k is the city-size value of the k neighbor cells. As we mentioned in the Materials section, cells with the portlocation attribute show different neighborhoods. Based on this equation and the work of Fotheringham (1981), we defined the centripetal and centrifugal forces as following:

$$V_i^1(t) = K_1 * \overline{P}_i(t)^{-\beta} \tag{2}$$

$$V_i^2(t) = K_2 * \overline{P}_i(t)^{-\alpha} \tag{3}$$

where V_i^1 and V_i^2 are the centripetal and centrifugal forces of cell i at time t, K_1 and K_2 are size parameters that control the formation of skewed values, and the β and α are scale parameters related to distances, i.e., they control the friction around the neighborhood. For example, if K_1, K_2, β, and α are set equal to one, then the dynamics of the model does not change in time. There is a constant pattern. On the other hand, if we modify one of the two scale parameters, the dynamics shows the formation of a type of normal statistical distribution. To generate skewed statistical distribution, we have to use the restriction in which $\beta > \alpha$ suggesting that the centripetal force is big enough to generate cities, but the centrifugal force is still working behind the centripetal. Next, the potential of growth is defined as following:

$$V_i(t) = V_i^1(t) - V_i^2(t) \tag{4}$$

where $V_i(t)$ is the trade-off between those forces. For example, if $V_i(t)$ is positive, then $V_i^1(t)$ predominates over $V_i^2(t)$. We are interested in this case; the centripetal force prevails over the centrifugal. Next, we have to compute the weighted average potential of the neighborhood, which is the following:

$$\overline{V}_i(t) = \overline{P}_i(t)V_i(t) \tag{5}$$

where $\overline{V}_i(t)$ computes the balance of forces, comparing the actual with the average potential. Finally, we compute the growth of each cell using the following equation:

$$P_i(t+1) = P_i(t)\left[1 + V_i(t) - \overline{V}_i\right] \tag{6}$$

where $P_i(t+1)$ is the update of the city-size value that depends on its actual value and the potential trade-off, which is the growth rate.

Initial conditions and data analysis

For simplicity, we used an array with a dimension (50,50). Each cell is associated with the city-size value in which $P_i(0) = random[1.0,1.01)$. This random number came from a continuous uniform distribution. We update the initial array 14 times to describe each of the simulations. It is important to mention that after this number of iterations, the model converges into a singular pattern, a point of attraction.

We started the analysis computing two reference cases: closed and open boundaries. Then, we computed three scenarios based on the port configuration (Figure 3). We applied an inferential data analysis to understand the effect of ports into the formation of a system of cities and to look for the emergence of skewed city-size distributions similar that the rank-size rule. We used a sensitivity analysis to compare different set

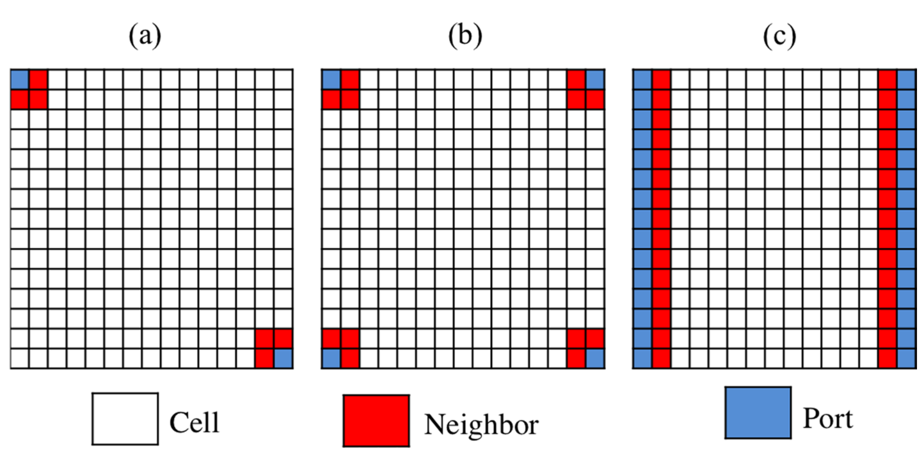

Fig. 3 Port configurations. Subfigure **a** is the basic two ports; subfigure **b** is the corner configuration; and subfigure **c** is the lateral configuration

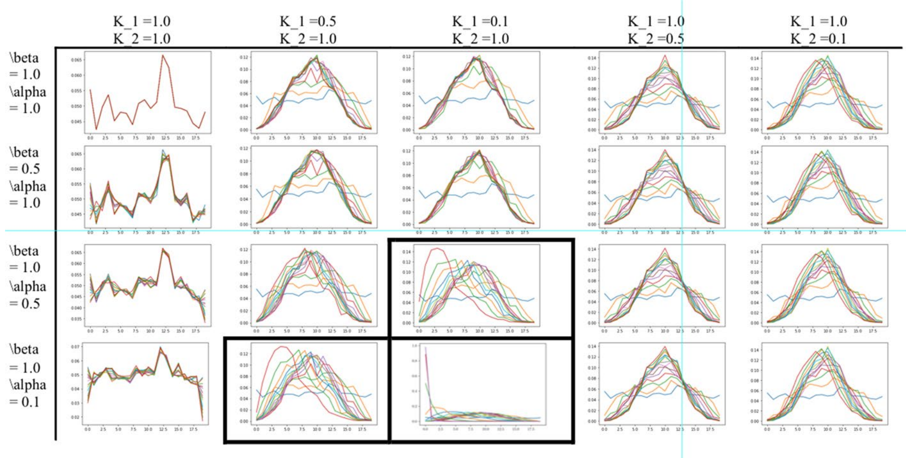

Fig. 4 Sensitivity analysis in the close boundary. The random seeds, based on a uniform distribution, were set to obtain the same initial arrays. Subfigures in lines show variations in the scale parameters, and columns show variations in the size parameters. Different colors in each plot represent iterations, starting from a uniform distribution. The model validation uses the parameters $K_1=0.1$, $K_2=1.0$, $\beta=1.0$, and $\alpha=0.3$

of parameters associated with the reference cases. The goal is to identify those parameters that better describe the formation of skewed statistical distributions related to the city-size values. Next, we validate our analysis, using such parameters, by comparing the based cases with the port configurations. In this case, the goal is to identify and measure the effect of ports into the formation of a city system based on its statistical distribution, skewness value, and the Spearman correlation.

Results

In this section, we present the findings related to the sensitivity analysis and the model validation. The former showed the statistical distributions of our cases associated with the change of scale and size parameters. These findings identified a particular set of parameters that we used to validate our approximation. Next, we compared the reference cases under the three port configurations. In all the cases, we used a random seed to set the same initial conditions in the array. Even the absence of a random seed our results hold (see the code and execute it with this modification in the OSF: Modeling ports and city-systems).

Sensitivity analysis

The sensitivity analysis showed the dynamics of our two cases associated with their statistical distributions (Figs. 4, 5). In particular, these figures showed the combination of parameters that produced different outputs, i.e., statistical distributions.

Figures 4 and 5 display different scenarios based on the variations of the scale and size parameters. Most of the patters are similar, however cases with a black square mark showed two important differences. The first is that the closed grid generates faster skewed distributions than the open case. This suggested that the boundary conditions matter to generate skewed distributions in the city-size values. The second is that the centripetal force dominates over the centrifugal. This result suggested that the restriction

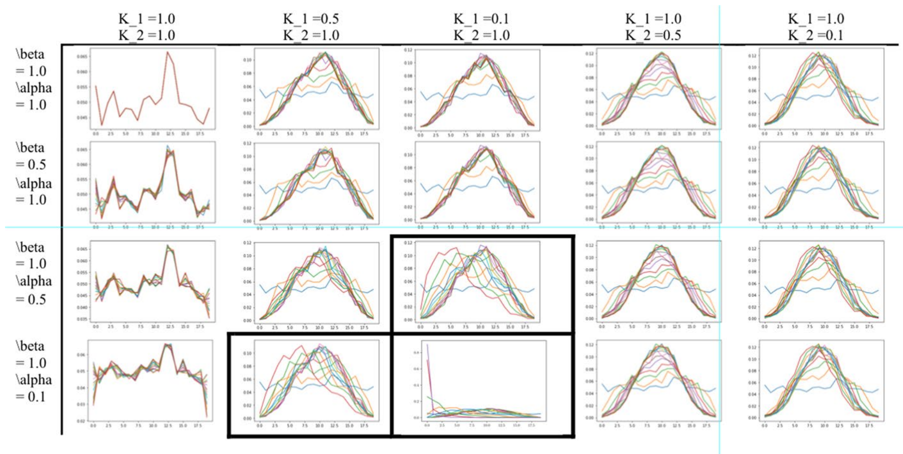

Fig. 5 Sensitivity analysis in the open boundary. The random seeds, based on a uniform distribution, were set to obtain the same initial arrays. Subfigures in lines show variations in the scale parameters, and columns show variations in the size parameters. Different colors in each plot represent iterations, starting from a uniform distribution. The model validation uses the parameters $K_1 = 0.1$, $K_2 = 1.0$, $\beta = 1.0$, and $\alpha = 0.3$

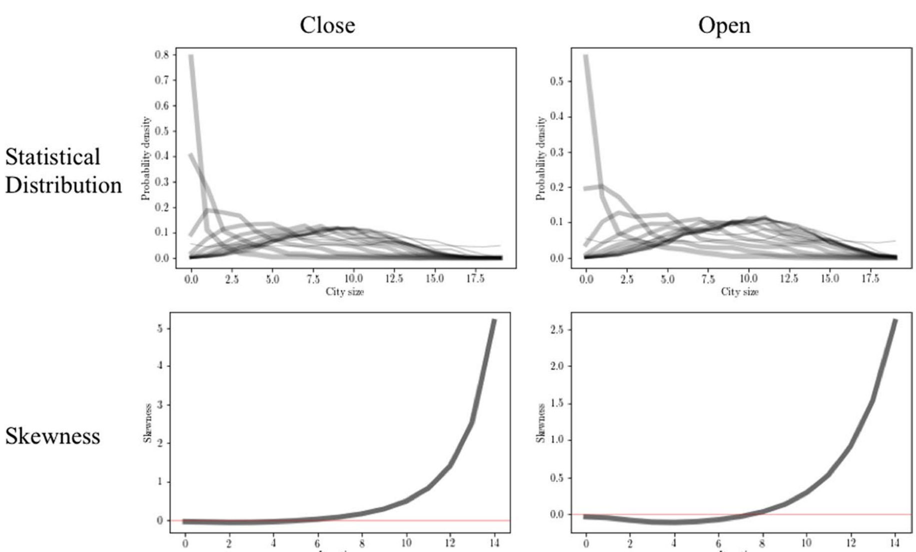

Fig. 6 Base cases. Dynamics of the statistical distributions and skewness. The skewness was computed by the Fisher-Pearson coefficient scipy.stats.skew. Each value of skewness is associated with each curve of statistical distribution per case

$\beta > \alpha$ is fundamental to generate bias distributions in city-size values. Therefore, we will use an intermediate case associated with the two black square subfigures in the column of $K_1 = 0.1$ and $K_2 = 1.0$.

Model validation

To exemplify the formation of skewed statistical distributions in our model, we present the selected case with $K_1 = 0.1$, $K_2 = 1.0$, $\beta = 1.0$, and $\alpha = 0.3$ (Figs. 6, 7 and Table 1)

Figures 6 and 7 show a comparison between different boundary conditions that generate skewed statistical distributions of the city-size values. The closed and open boundary conditions represent the extreme cases, and they showed the expected

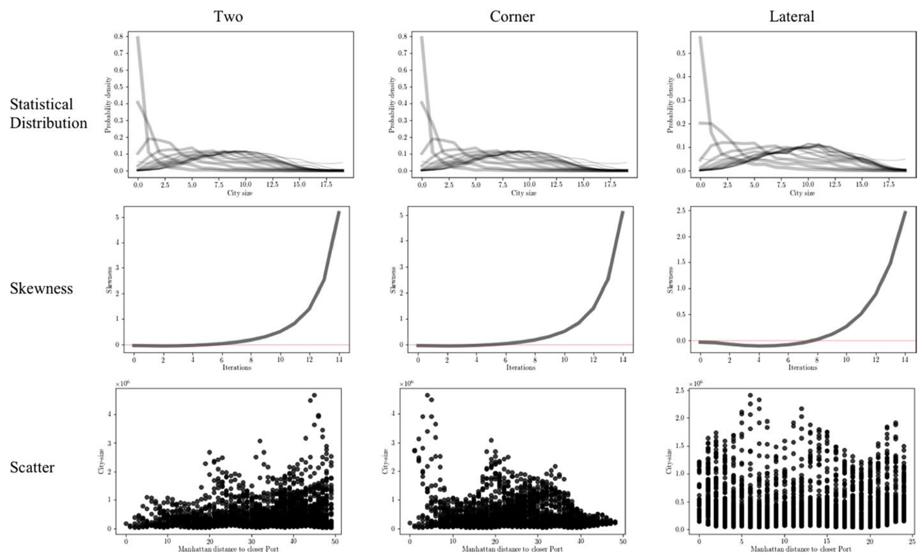

Fig. 7 Port configurations. Dynamics of the statistical distributions, skewness, and correlations. The skewness was computed by the Fisher-Pearson coefficient scipy.stats.skew. Each value of skewness is associated with each curve of statistical distribution per case. Scatter plots: (x-axis = Manhattan distance to closer port, y-axis = city-size)

Table 1 K-S test and best fit parameters of the based cases and the port configurations

Statistical	Closed Exponweibull	Open Lognormal	Two Lognormal	Corner Exponweibull	Lateral Lognormal
Distributionks-test	(0.0857, 0.8553)	(0.1168, 0.4736)	(0.1168, 0.4736)	(0.0857, 0.8553)	(0.1168, 0.4736)
Best fit	(4.1411, 0.5415, 28,518.8760, 96,076.2683)	(10.7450, 34,195.3987, 11.8154)	(11.2687, 34,195.3987, 6.5101)	(3.7110, 0.5548, 33,491.4490, 106,816.1286)	(10.7428, 34,195.3987, 11.8124)
Spearman correlation	NA	NA	(0.1092, 8.0638e−08)	(− 0.0488, 0.0166)	(0.0019, 0.9253)

KS test and Spearman correlation: (value, p-value). Estimated parameters of best fit: (parameters, loc, scale). The exponentiated Weibull (exponweibull) distribution shows a probability density function of the form $f(x,a,c) = ac[1 - exp(-x^c)]^{a-1} exp(-x^c)x^{c-1}$ where $x > 0, a > 0, c > 0$. The lognormal distribution shows a probability density function of the form $f(x,s) = \frac{1}{sx\sqrt{2\pi}\exp}\left(-\frac{\log^2(x)}{2s^2}\right)$ where $x > 0, s > 0$

skewed distributions (Fig. 6). As we mention above, the closed boundary generated faster skewed distributions than the open boundary case (see the skewness results). In particular, from time 0 to 6, in the closed boundary, the value of skew indicated symmetric distributions. After time 6, the value of skew indicated that the tail is on the right, asymmetric distributions. On the other hand, in the open case, from time 1 to 7, it showed negative values of skewness. After time 7, the value of skewness increased rapidly. Closed and open cases are best described by the exponentiated Weibull and lognormal statistical distributions respectively. On the other hand, the port configurations displayed intermediate cases of statistical distributions between our based cases (Fig. 7). The Two and Lateral results showed similar best-fit distributions, lognormal, but visually the former was more biased than the latter. This finding suggested that both cases have a similar data generating process in which the port location matters to generate types of statistical distributions. The Corner configuration showed similar best-fit results as the open based case, exponentiated Weibull, suggesting a similar data generating process based on different initial configurations. Therefore, we implied an effect of ports into the formation of skewed statistical distributions.

With regard to port configuration dependence, in Fig. 7 and Table 1, differences among Two, Corner and Lateral configurations are shown for the selected case. The Two port configuration showed a positive correlation between the Manhattan distance to closer ports and the city-size values. This result implies that as distance to ports increases, so do the city-size values. Its suggested that small number of ports generate a system of cities where higher values of the city-size were far from maritime transport nodes. The Corner configuration showed a negative correlation suggested that an small increment of ports in the region switched the city-size behavior, i.e., higher values of the city-size were close to ports. The Lateral configuration showed a positive but small correlation coefficient. It suggested that a large number of ports continues to affect the city-size values, even though their correlation is small. This type of result is consistent with the findings showed in the work of Lugo et al. (2020) in which their empirical data displayed a weak relationship between the city-size and the distance from a city to its closest port. Overall, our model dynamics results unravel different scenarios of the effect of ports in the formation of a system of cities showing skewed values of city-size. Therefore, the number and location of ports affected the emergence of skewed statistical distributions in urban systems.

Discussion

Our theoretical study has described how the existence of ports affects the growth of a system of cites generating skewed statistical distributions in their city-size data. In particular, an increasing number of port cells along boundaries boosted the connectivity of regions, i.e., the discontinuity diminished. These port cells affect city growth rate and location. This result may be explained by the fact that ports are not isolated transportation nodes. They are part of different interrelated networks—for example, economic, urban, and geospatial—in which a small perturbation generates unexpected large-scale results. An interpretation of this result is that ports might be not only peripheral compared with the inland city centrality, but also to coastal urban primacy. Therefore, boundary conditions related to port cells matter to generate skewed values in a system with similar parameters.

Notice that our first assumption in the introduction: an increasing number of port sites generates a system of cities characterized by the common city-size distributions in which the location of cities is randomly determined, was validated in our findings. In particular, Fig. 7 and Table 1, the scatter plot and the Spearman correlation of the Lateral configuration confirms it. We interpreted it as a real-world empirical fact. Even though the correlation coefficient was weak, the effect of ports to the city-size and its location in a system of cities is consistent with that of Lugo et al. (2020) who presented an empirical analysis. On the other hand, the second assumption: a decreasing number of port sites generate a system of cities showing less skewed city-size distributions and displaying strategic locations of cities close to these transport nodes, was only partially validated by our findings. The first statement in this assumption was not true; instead, we found that small number of ports still generated skewed statistical distribution of city-size. A possible explanation for this result is that the interaction of cities based on their geospatial, economic, or urban attributes is higher than the effect of increasing or decreasing the number of port sites—i.e., there is an urban primacy. However, the second statement of this assumption was confirmed; depending on the number of ports and their location, values of the city-size and their location were close or far from ports. We interpreted it as a common behavior in the spatial coordination between cities and ports. That is, the existence of a small number of ports, for example in ancient times, showed small effects of systems of settlements in regions. This type of systems depended on inland transport networks for surviving and developing. Conversely, the existence of a large number of ports nowadays showed significant effects of systems of cities in their size and location. In terms of transport and urban geography, small and medium cities are important nodes in the transportation system, located between large cities and their closest ports.

Concerning the questions also posed in the introduction our answers are the following. Any place in the edge of the grid (representing by coastal areas) has the potential to become port-city. The development as a port depends on historical events associated with ancient settlements that were into or close to natural harbors. This result is a possible explanation for describing the dynamics of developing port sites. For example, different ancient economies—the Roman and the Aztec empires—could share similar processes associated with their port sites. On the other hand, the development as a city depends on the trade between particular areas to others and the type of transportation system that connects inlands to maritime routes. These characteristics are positively related to the city-size value. Therefore, our formulation described how local effects of ports generate a system of cities with skewed values in their city-size, even though our model is deterministic in the location of ports.

The location of ports affects the growth of the city-size because an increased number of ports connect better discontinuous landscapes. Such an effect of ports in cities may vary substantially according to the type of cargo, the port performance, hinterland connectivity, and the size of different economic and transport activities. This result may be explained by the fact that ports as transport nodes increase the possibility of cities to trade with long distance regions and countries. This connectivity impacted the spatial organization of the system of cities due to, in some cases, higher values of the city-size are located closed to port cells. However, the existence of higher values far from port location was possible but in less number. Therefore, the location of ports affects the growth rate of the city-size values and the spatial organization of the system generating clusters or regions with high density of city-size values.

Based on the parameters used in "Model validation" section, we concluded that port locations were apparently related to the emergence of skewed statistical distributions. Depending on the type of port configuration, the system of cities showed different levels skewness in the city-size values. In particular, higher number of port cells decreased the speed on the formation of skewed values. Therefore, our modeling suggests that ports affect the dynamics of the city-size distribution generating hierarchies into an urban system.

Conclusion

Our work deals with the evolution of a system where space and time are dealt with on an equal standing. Several formalisms have been developed to tackle such spatio-temporal evolutions, e.g., spatially coupled systems of ordinary differential equations (continuous state variables, continuous time and discrete space), coupled map lattices (state variables continuous, time discrete and space discrete) partial differential equations (state variables, time and space continuous), and CA (state variables, time and space discrete). Following a suggestion by Batty (2005), here, to our knowledge for the first time, we present a CA model for the dynamics of portcity problem we are studying. This is the main methodological contribution of the paper. Since we are looking at global properties of a coarse-grained description, the CA formalism is ideal for retrieving essential dynamical and statistical features, dependent on the range of interactions, time scales, transients, symmetry considerations, geometry diversity, variety of boundary conditions and inhomogeneities. Besides, CA simulations are computationally efficient, straight forward, transparent with explicit space and time dependences. Our work contributes to the existing knowledge of the formation of the city-size distributions based on CA simulations. It describes the dynamics of the city-size distribution based on the spatial interactions between ports and cities. These interactions are supported by the ideas and theoretical formulations mentioned in the section of Literature review. In particular, we incorporated ideas provided by Fujita and Mori and updated Krugman's formulation for modeling the location of ports into a square grid. Moreover, we used the definition of port-city to set initial conditions and the neighborhood of each port-city cell. Our model is deterministic, discrete, synchronic, has one temporal scale, and requires a small number of iterations to attain steady-state dynamics. Our study cases showed the effect of grid boundary conditions, with ports distributed with different symmetry configurations. In particular, the two port-city configuration has one axis of specular symmetry, the four port-city has two specular symmetries, and the lateral port case showed cylindrical symmetry. With the above considerations our model exhibits at a generic level concordance between our theoretical study and empirical data. We should remark, however, that our formulation does not pretend to classify specific regions and cities therein. The model can be extended to more realistic situations by adding more specific information such as more precise, explicit local and global interactions, more relevant parameters, different grid geometries, and types neighborhoods. Such a program may be explored in detail for more specific spatio-temporal dynamics between ports and cities. A further study focussed on testing our model with empirical evidence is therefore suggested.

Summing up, the number of, and the location of, the ports contributes to the analysis of the city-size distribution. Port sites are more than transport nodes in the transportation system. Depending on their number and location, the city-size values show different types of correlations. For a small number of ports within the model a positive correlation between size and port distance is found—i.e., the central place configuration. On the other hand, as the number of ports increased, a negative correlation surfaces with an increase in city-size values closer to the ports—i.e., the coastal-urban primacy configuration. Finally a dense port distribution produces homogeneously spaced location between ports and cities. These findings may encompass most of the empirical cases, for example islands and diverse regions. Ports play multiple functions that have affected the development of countries and regions. Our approximation may explain some aspects of empirical data of the city-size distribution related to ancient civilizations and current societies.

The study of the formation and development of city systems is a complex process. In this paper we adopt a complex systems approach to analyze the influence of ports on this process. One of the hallmarks of complexity is multifactoriality. As a first step, in our work, the factor we focus on is the presence of ports. The purpose of the study of a complex system is to simplify problems, unravel the main elements that give rise to essential behaviors that are generic and applicable to a wide set of circumstances. Many other factors contribute to our findings, for example environmental conditions, hinterland effects, multiplicity of time scales and transport networks, to mention a few. The possibility of extending this study to multilayer networks is enticing. These considerations will undoubtedly improve our modeling; however, it is important to remark that our model as it stands is able to recover general aspects of empirical studies and is consistent with previous theoretical results. The generic nature of our modeling provides a testing ground for different scenarios, with adjustable parameters ad hoc for the analysis of a vast set of empirical studies. The possibility of classifying different systems with our model or even forecasting city system scenarios is an open challenge.

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Author contributions
IL proposed the main conception and design of the manuscript, analyzed data, interpreted results, written the python programing code, written the final manuscript. GMM proposed and contributed with ideas to clarify the manuscript, participated in the discussion, revised and written the final manuscript. All authors read and approved the final manuscript.

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Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
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Competing interests
The authors declare that they have no competing interests.

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