Spatial Rules Generate Urban Patterns: Emergence of the Small-World Network

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LECTURE NOTES IN GEOINFORMATION AND CARTOGRAPHY

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A. Ruas · C. Gold (Eds.)

Headway in Spatial Data Handling

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The symposium places particular emphasis on identifying significant headway in GIS. The papers published are carefully refereed by an international programme committee composed of experts in various areas of GIS who are especially renowned for their scientific innovation. The proceedings of this series have become an important reference for researchers and students in the field of geography, cartography and geoinformation.

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Anne Ruas · Christopher Gold (Eds.)

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13th International Symposium
on Spatial Data Handling

Springer

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Foreword

Geographic information is a key element for our modern society. Put sin ply, it is information whose spatial (and often temporal) location is fund mental to its value, and this distinguishes it from many other types of dat and analysis. For sustainable development, climate change or more simp resource sharing and economic development, this information helps to f cilitate human activities and to foresee the impact of these activities space as well as, inversely, the impact of space on our lives. The Intern tional Symposium on Spatial Data Handing (SDH) is a primary researc forum where questions related to spatial and temporal modelling an analysis, data integration, visual representation or semantics are raised.

The first symposium commenced in 1984 in Zurich and has sinc been organised every two years under the umbrella of the Internation Geographical Union Commission on Geographical Information Scienc (http://www.igugis.org).

Over the last 28 years, the Symposium has been held in:

1st - Zürich, 1984
2nd - Seattle, 1986
3rd - Sydney, 1988
4th - Zurich, 1990
5th - Charleston, 1992
6th - Edinburgh, 1994
7th - Delft, 1996
8th - Vancouver, 1998
9th - Beijing, 2000
10th - Ottawa, 2002
11th - Leicester, 2004
12th - Vienna, 2006

This book is the proceedings of the 13th International Symposium c Spatial Data Handling. The conference was held in Montpellier, Franc on June 23rd to 25th 2008, in conjunction with and prior to SAGEO, the a nual French conference on Geomatics. All the papers in this book we submitted as full papers, and received blind reviews from three membe of the Programme Committee. 63 papers were submitted and the 36 th are included here are of a high standard, as well as being accessible to ev ryone who is doing research in the science of geographical informatio This year we have chosen to promote the five best reviewed papers th can be noted by a * on the table of contents. These very enthusiastic an original papers deal with ontology, classification, data matching, 3D and spatial process description.

This publication 'Headway in Spatial Data Handling' is the fourth in the Springer-Verlag series which members of the commission hope will continue successfully in the future.

Acknowledgements

This conference has been organised by a network from four geographic locations: Montpellier (Thérèse Libourel), Brest (Thomas Devogele), Pa (Anne Ruas) and Wales (Chris Gold).

We thank all the members of the Programme Committee for their extr ordinary effort to return detailed reviews on time.

We warmly want to thank Nicolas Moyroud for helping us with the w site with a constant and positive availability, Thomas Devogele for editi and for his contact with the publisher and Therese Libourel for her ener in organising the conference in Montpellier (and for editing the Lat files).

A special thank you to Victor for enhancing the pleasure of our worki together.

Anne Ruas and Chris Go
31 March 20

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Spatial Rules Generate Urban Patterns: Emergence of the Small-World Network

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Abstract

Objective explanation of urban patterns requires regeneration of these patterns. We defined eight simple spatial rules for locating a building in space and used these rules to simulate re-generation of the small-world network pattern, which is an archetype in structures of cities. We provided a spatial description of how these rules act generating the mentioned pattern. The description is based on using local spatial predictability of the physical reality, incorporating basic spatial global rules, and reducing the indeterminacy of the simulation model. The results show that following the spatial rules derived from the physical reality, it is difficult to avoid generating the small-world network. This clarifies problem of the urban design approaches damaging the small-world network patterns in contemporary cities. The results also propose the small-world network characteristics for cities that are not pre-planned, or more properly organic cities, settled on flat lands.

Keywords: Small-World Network, Spatial Rule, Physical Reality

1 Introduction

Although each city has unique story (Lynch 1981), archetype patterns exist in cities (Salingaros 1998; Hillier, 1989; Hillier, 2001; Carvalho and Penn, 2004; Alexander 2002a, 2002b). Human beings interaction with each other and especially their interaction with the physical reality (the sun, topography, winds, water, and food resources) to derive the maximum utility from living together generate these patterns.

Complexity of cities makes it difficult to investigate the urban patterns and their real causes. This usually leads us to subjective explanations, dominated by political and economical issues. Objective explanation of complex urban patterns requires regeneration of these patterns through effective incorporation of spatial rules.

We studied eight simple spatial rules and the patterns they generate in a simulated cellular environment. These rules are: 1) *Distance-to-Center-of-Gravity*, 2) *Distance-to-Road*, 3) *Free-Space*, 4) *Share-Free-Space*, 5) *Adjoining-Free-Space*, 6) *Access-Space*, 7) *Adjoining-Access-Space*, and 8) *Sun-Position* rule. The rules are selected based on:

1. Simplicity which enables more clear description and justification of the results and interaction of rules[1];
2. Inclusion of rules from related work. Hillier (1989) introduced *Free-Space*, *Share-Free-Space*, and *Adjoining-Free-Space* rules and showed that they can regeneration the beady ring pattern which is an archetype pattern in cities[2];
3. Similarity of the patterns they generate to the reality which is discussed and visually validated by urban designers[3]. This validation provides an overall test of wholeness of the rules[4].

[1] For example among different hypothesis of how a human define nearness and farness, we used Euclidean distance. We will select more complex hypothesis when this one failed generating the patterns we expected.

[2] The beady ring pattern depicts "...constant variation in the width of the open space so fatter areas of space are linked to other fatter areas through thinner spaces. (Hillier 1989, p. 339)"

[3] Urban designers are more familiar with the structural geometric patterns of cities than urban planners and urban architectures. Urban design acts as a mediator and sits at the interface between urban architecture and urban planning. Urban architecture and planning focus on artistic and socio-economic factors and urban design emphasizes on physical attributes that usually restrict its scale of operation to arrangements of streets, buildings, and landscapes (Batty et al. 1998).

[4] Alexander's wholeness viewpoint (Alexander 2002a and 2002b) are adopted·

4. Increasing determinacy of the simulation model using the local spatial predictability of the physical reality. This quality of space is missed or underestimated in previous studies, like Hillier (1989) and Lechner et al. (2006), for they incorporated the physical reality, but as a second-class entity. They firstly simplify space (for example to a horizontal and isotropic space) by removing or reducing the complexities produced by the physical reality. After defining their rules in the simplified space, artificial random processes are used to reconstruct the removed complexity of space. Providing a deterministic model using the local spatial predictability, we considered the sun and pre-existent roads (the effects of access to sun light and roads) here[5];
5. Depicting inseprability of macro and micro world. We defined two basic global rules: *Distance-to-Center-of-Gravity* and *Distance-to-Road* are global rules. It is intended that the global rules be neutral and not being selected to exert any specific pattern[6] and the patterns be generated through interaction of rules, especially local rules. Then we admit explicit global rules only and also test the expected rule-set for generation of different patterns. These will reduce the risk of defining global rules which may dominate the local rules or exert specific patterns.

Our target pattern here is the small-world network pattern. It is an archetype in cities (Salingaros 1998). In the small-world network each node can reach most of the other nodes in short steps, despite they are not neighbors.

The small-world network pattern brings out the required level of connectivity to support life in a city (Salingaros 1998). This pattern represents dynamicity, stability, scale independence, and power-law distribution in a structure, like World Wide Web, social networks, and urban geometric structures. Investigation of the small-world network will provide us with a basis to study emergence of other urban patterns like Zipf's law distribution of length of passages (Carvalho and Penn, 2004) and fractal patterns.

We defined thirteen plausible rule-sets from the mentioned eight rules. These rule-sets are numerically evaluated to define how they generate the small-world network pattern. For each simulation, the graph that represents connections of the simulated free spaces (and the pre-existent roads) are created. Then the mean-shortest path length and the clustering coefficient of the graph are calculated and compared with the trend of the small-world network. Besides, we investigated the scale-freeness quality of the patterns

[5] We will let in other characteristics of the physical reality like topography in further work.

[6] That the rules do not exert specific patterns are considered in definition of lo-

comparing the degree-distribution of their graphs against the power-law distribution and checking stability of its exponent while the patterns grow.

The rules and rule-sets presented in this paper provide one of the possible descriptions for the small-world network pattern of cities. It is intended to clarify the role of spatial rules and geometric structure of cities in bringing life to cities and enrich the urban designers' knowledge about what rules generate cities.

The paper includes 7 sections. The small-world network is described in section 2. Section 3 explains the simulation model. The global and local spatial rules are introduced in section 4 and also their validation process is discussed. The determinacy of the simulation model is described in section 5. Section 6 numerically evaluates emergence of the small-world network pattern in the model. In the end, conclusions are presented in section 7.

2 The Small-World Network

Small-world network is a class of random networks that its nodes are connected by both long and short links (Salingaros, 2001). Then each node in the small-world network can reach most of the other nodes by a small number of steps, although most of the nodes are not neighbors (Fig. 1).

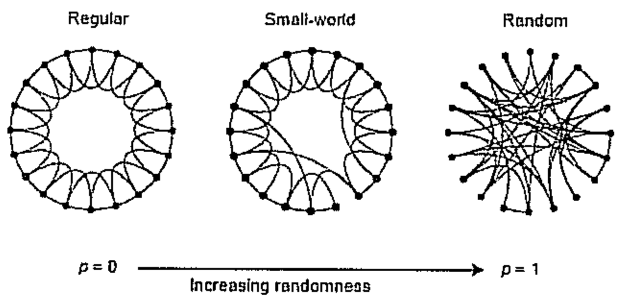


Fig. 1. The small-world network stands between a regular and a random network. It is highly clustered like a regular graph, yet with small characteristic path length, like a random graph. Here p represents the probability of connecting a node/vertex to far nodes/vertices, rather than immediate nearest neighbor nodes. It is defined by node's degree. In this figure, nodes have 4 degrees[7] (Watts and Strogatz, 1998).

[7] The proposed method by Watts and Strogatz (1998) for generation of a network with specific probability p is to rewire a fully regular graph. They introduce the rewiring process as "We choose a vertex and the edge that connects it to its to a vertex chosen uniformly at random over the entire ring, with duplicate edges forbidden; otherwise we leave the edge in place. We repeat this process by moving clockwise around the ring, considering each vertex in turn until one lap is completed. Next, we consider the edges that connect vertices to their second-nearest neighbours clockwise. As before, we randomly rewire each of these edges with probability p, and continue this process, circulating around the ring and proceeding outward to more distant neighbours after each lap, until each edge in the origi-

Watts and Strogatz (1998) compared the mean-shortest path length and the clustering coefficient of regular, small-world, and random networks. They define the mean-shortest path length as "... the number of edges in the shortest path between two vertices, averaged over all pairs of vertices. (Watts and Strogatz, 1998)" The clustering coefficient is also defined as the average of edges exists between neighbors of a vertex to maximum number of edges between them over all vertices. The maximum number of edges that can exist between the n vertices is $n*(n-1)/2$ for an undirected network.

Watts and Strogatz (1998) showed that the mean-shortest path length of a small-world network and random networks are similarly small, but the clustering coefficient of a small-world network is larger than what is expected for random networks (Fig. 2). It means that a small-world network has few high degree nodes, known as hubs, and the rest of the nodes are peripheral, low degree nodes. It brings stability against changes may happen in the peripheral nodes. It makes the small-world network pattern reliable enough to support life of networks like World Wide Web or a city.

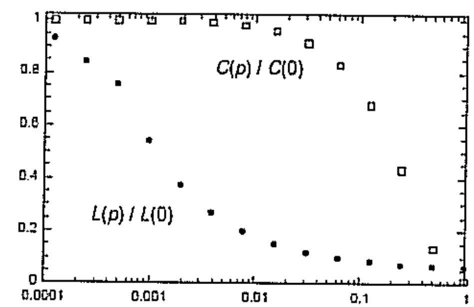


Fig. 2. The mean-shortest path length $L(p)$ and the clustering coefficient $C(p)$ for the family of randomly rewired graphs with 1000 nodes which have 10 degrees. The x-axis represents the probability of networks (p) in logarithmic scale. The values are normalized using $L(0)$, $C(0)$ for a regular lattice. (Watts and Strogatz, 1998)

Degree-distribution of the small-world network fits the power-law distribution. It means that the small-world network is scale-free. The small-world network also encourages movement for it inherits the predictability of regular networks and accessibility of random networks.

For a network of spaces in a city, the mean-shortest path length represents how far you should go to be able to reach urban facilities like stations and shops. The clustering coefficient reflects how stable and reliable these accesses are, considering the continuous changes may happen due to human activities, like accidents or constructions, or environmental conditions (e.g. bad weathers) that can hinder or block normal flows in a city. These are the basic characteristics of an urban structure which is alive (Salingaros, 2003).

Improving the damaged small-world network pattern of our contemporary cities, Salingaros (2003) encourages expansion of short links (pedestrian) among the mostly long links (motorway roads) that have already overcome our cities. It is also considered as an alternative to improve the pedestrian passages in cities or even design pedestrian cities. Although it seems that we mastered developing long links like motorways while destroying short links, the current problem is how to do the reverse and expand short links and how to handle the interactions between these mediums of transportation. Filling the gap here, we need to develop our objective knowledge about what causes what (Salingaros, 2003). The question is how pedestrian passages are generated and interact with other mediums of transportation like motorway roads and subways.

In the simulation model presented in this paper, we considered pedestrian passages and motorway roads as our transportation mediums. This case is typical in historical cities that have many short pedestrian links and a few long motorway links usually connect two or more cities together (Lynch 1981, Salingaros 2003, Alexander 2002a). Considering this and the entities of the physical reality we are using (the sun and pre-existent roads or more properly the effects of access to sun light and roads), we expect that simulations become more similar to structure of cities that are not preplanned rather than our contemporary cities[8]. Urban designers name these cities as organic cities (Lynch, 1981).

[8] Then the results do not prescribe solutions for our contemporary cities, but describe what is missed or underestimated. They provide urban designers with more objective description of patterns of cities. It can help in developing more effective

3 Simulation Model

We used a cellular simulation environment. Each cell can be empty or represent a building, a free space, or a road.

The free spaces emerge during simulation. They generate the pedestrian passages between the buildings.

Roads are pre-existent entities in the environment. The width of the roads is fixed at one cell (which is equal to the width of the generated pedestrian passages) to avoid the possible influence of changing width of the roads.

Each simulation starts by putting one or more buildings as seeds in the environment. At each step of the simulation, one building is added to the environment using the rules discussed in the section 4 and considering the buildings already located. Accumulation of the buildings generates the urban patterns.

The proposed simulation approach is a space allocation. It is not an agent-based simulation that is being used for simulation of human decisions (Epstein and Axtell, 1996). Using jargon of the agent-based simulations, however, the proposed simulation would be an agent-based simulation that uses a multitude of agents act in a queue (sequentially and not simultaneously) and accumulate their decisions in the environment. No memory and learning is required here.

4 Rules Validation

The simulated patterns using the eight rules, which are introduced in this section, were presented to four urban designers[9] and they were asked whether the patterns are meaningful or not. The invalidated rules were dropped[10].

Among the rules, *Distance-to-Center-of-Gravity* and *Distance-to-Road* are global rules and the rest are local rules. The *Distance-to-Center-of-Gravity* rule and the *Free-Space* rule are the basic rules, which are used in most of the simulations by default[11]. In the figures shown hereafter, building seeds are shown in dark gray, buildings in gray, roads in light gray, free spaces in white and empty spaces in black.

[9] Two PhD and two MSc scholars.

[10] We did not discuss here the rules that are not validated.

4.1 Distance-to-Center-of-Gravity

This rule asserts that people prefer to live near each other (Tobler, 1979). In its simplest form, the rule formulates that the sum of the inverse distances from a location to all the buildings already exist in the environment affects the value of the location for adding a new building (Eq. 1). It is the distance to the gravity center of the buildings (Fig. 3a).

$$Value\text{-}of(aLocation) = \sum_{aBuilding}^{Buildings} \frac{1}{Distance(aLocation, aBuilding)} \quad (1)$$

This rule aggregates the buildings, defining the feasible locations with maximum value among the immediate neighbors of the buildings already exist. It forms a layer-by-layer pattern (Fig. 3b).

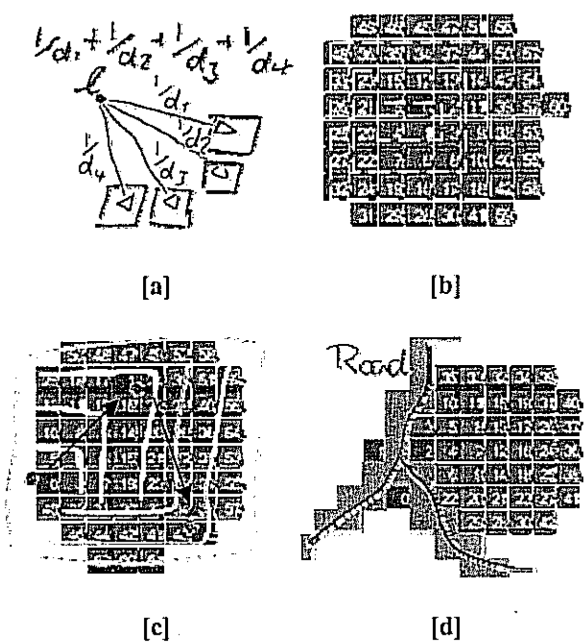


Fig. 3. [a] Schematic representation of the Distance-to-Center-of-Gravity rule. It values each location of space as sum of its inverse distances to existing buildings. [b] This rule creates layer-by-layer patterns around the seed placed in the environment by the user. [c] When detached seeds are used to initiate the simulation the generated pattern moves like a wave to cover all seeds. [d] This pattern can not pass entities like roads.

Starting the simulation with more than one seeds, the pattern starts from

wave-like towards the other closest seed and continues until include other seeds (Fig. 3c). After that, the pattern grows as described for Fig. 3.b.

Any entities that occupy parts of the outer layer of an aggregation of buildings will block further growth of the pattern at those parts (Fig. 3d). Then a road will behave as an impassable edge against this rule, while in reality a road may hinder the crossing but does not block it.

4.2 Distance-to-Road

This rule says that distance to the roads affects the value of the location for adding a new building (Fig. 4a). It maximizes the inverse distance of a location to the road (2).

$$Value\text{-}of(aLocation) = \max\left(\bigcup_{aBuilding}^{Buildings} \frac{1}{Distance(aLocation, aBuilding)}\right) \quad (2)$$

This rule aggregates buildings around the roads. The pattern grows layer-by-layer along the roads (Fig. 4b). Unlike the *Distance-to-Center-of-Gravity* rule, the roads behave here as passable edges.

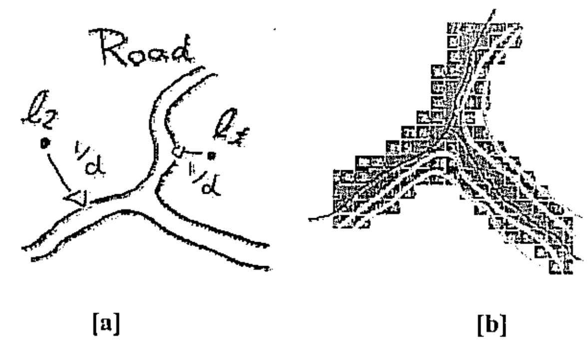
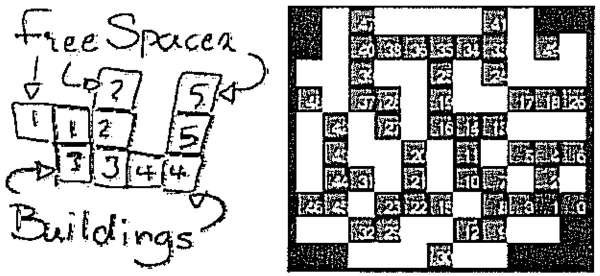


Fig. 4. [a] Schematic representation of the Distance-to-Road rule. It values each location (l) based on inverse shortest distance to roads. [b] This rule creates layer-by-layer patterns, defined by the parallel lines, around the roads.

The value derived using this rule just depends on the shape of roads and the location in the environment. So this value is static and does not change after adding new buildings. But the value derived from the *Distance-to-Center-of-Gravity* rule increases through the time. Then combining these two rules, their values are normalized.

4.3 Free-Space

Hillier (1989) introduced *Free-Space* rule as each building should have an exclusive free space attached to it (Fig. 5a and 5b). This free space is sort of a front yard. The free space enables going in and out of a building.

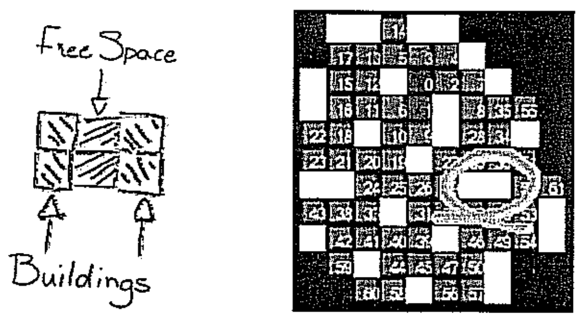


[a] [b]

Fig. 5. **[a]** Schematic representation of the Free-Space rule. **[b]** This rule is the basis of other local rules defined here.

4.4 Share-Free-Space

Hillier (1989) introduced this rule. It says that free space of a building can be shared between and among two or more other buildings (Fig. 6a). The main effect of this rule is compactness of the free spaces (Fig. 6b).



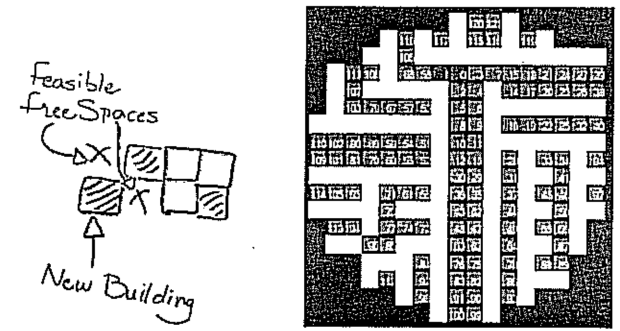
[a] [b]

Fig. 6. **[a]** Schematic representation of the Share-Free-Space rule. It discards assignment of new free space to a building if any free spaces still exist in 4 neighbors of the building. **[b]** Compacting the free spaces, this rule also creates enclosed detached free spaces like what is marked in the figure.

It also generates rows of buildings formed by pair of buildings, which are located back to back. This pattern is more realistic than the patterns generated by sole usage of the *Free-Space* rule that generates rows of building from single buildings located side by side. This rule may also generate detached free spaces bounded by buildings, like an exclusive passage in a building complex (Fig. 6b).

4.5 Adjoining-Free-Space

Hillier (1989) introduced this rule that forces a free space to adjoin other free spaces, if possible (Fig. 7a). Emergence of terraced buildings is the main effect of this rule (Fig. 7b).

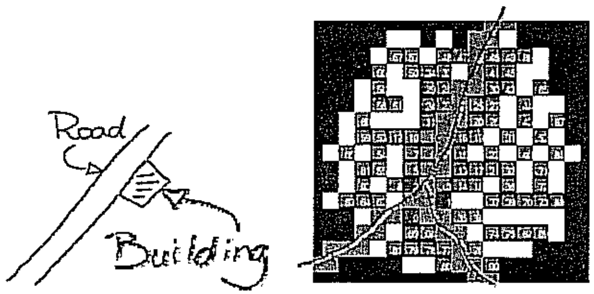


[a] [b]

Fig. 7. **[a]** Schematic representation of the Adjoining-Free-Space rule. **[b]** It creates terraced buildings.

4.6 Access-Space

This rule says that a road can provide its neighbor buildings with their required free spaces (Fig. 8). The neighbor buildings share the road as their free spaces. Their entrances face toward the road. This rule creates more real patterns around the roads than using the *Distance-to-Road* rule alone. It also compacts free spaces along the roads. The *Access-Space* rule causes roads to behave as passable edges even when rules like the *Distance-to-Road* are not used.



[a] [b]

Fig. 8. **[a]** Schematic representation of the Access-Space rule. **[b]** This rule causes compaction along the roads. It enables the pattern to pass the roads.

4.7 Adjoining-Access-Space

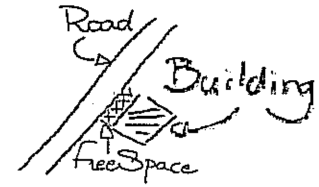
This rule states that the buildings that are near a road tend to face toward the road. These buildings use the gap between themselves and the road as their free spaces (Fig. 9a). The expected effect of this rule is near-road buildings that follow the shape of the road (Fig. 9b). The free space of these buildings somehow widens the road and looks like sidewalks.

Emergence of these near-road buildings, however, is not strict. The locus of the feasible locations to apply this rule is just the two cells buffer of the roads. No specific rule entails location of building in this locus.

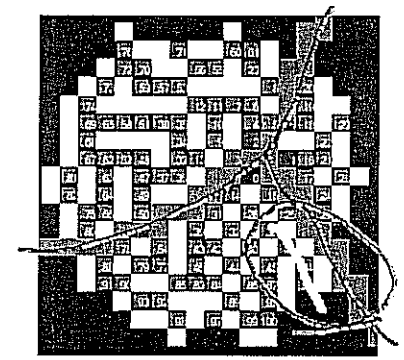
It seems that the *Distance-to-Road* rule can overcome this situation, but it firstly fills the first layer of buildings adjoining the road (one cell buffer of the road). So practically, the second layer that contains the expected locations for the *Adjoining-Access-Space* rule will be blocked and it can not be applied for them.

Adding the *Distance-to-Center-of-Gravity* rule, we can avoid filling all locations in the first layer which is adjoining the roads. This provides the opportunity of locating the near-road buildings.

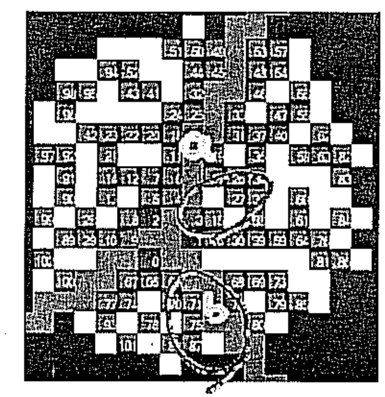
In this situation, adding other rules like he *Access-Space* rule will affect the pattern and location of the near-road buildings. Then retreated buildings (Fig. 9c{a}) or rows of buildings along a road (Fig. 9c{b}) may emerge.



[a]



[b]



[c]

Fig. 9. **[a]** Schematic representation of the Adjoining-Access-Space rule. **[b]** It creates buildings parallel to roads and **[c]** retreated buildings, marked as {a}, and rowed buildings, marked as {b}.

4.8 Sun-Position

This rule holds that each building tends to attain the maximum sun light in their attached free space. Then we assign the free space of a building based on the cardinal directions. The directions are prioritized as south, east, west, and north (Lynch, 1981). This rule discards any random selection of free spaces.

5 Determinacy of the Simulation Model

Although the free spaces can be located deterministically using the *Sun-Position* rule, still we are using a random generator to locate the buildings. It seems that deterministic location of buildings should be satisfied through combination of rules.

We just discussed location of buildings (not the free spaces) in the next two sub-sections. The point is to define how the rules distinguish locations of buildings. At each iteration, we count the ties that are the locations which have the same value equal to the maximum value (1 and 2). One of these locations should be selected for putting a new building. Then higher determinacy will be achieved if the number of ties decreases.

5.1 Global Rules

The *Distance-to-Gravity-Center* rule provides the simplest pattern. It causes the highest level of indeterminacy (Fig. 10). The number of similar ties varies from 1 to 8 (Fig. 10a). When there is more than one seed the process shows higher determinacy (Fig. 10b and Fig. 10c) until the pattern includes all the seeds. Then the determinacy decreases and become similar to the simulation with one seed (Fig. 10a). Sole usage of the *Distance-to-Road* rule causes high indeterminacy, as there are many locations with similar shortest distance to roads (Fig. 11).

Using the *Distance-to-Gravity-Center* rule and the *Distance-to-Road* rule together the number of similar locations reduces to 2-3 locations (Fig. 12). The *Distance-to-Road* rule increases the determinacy, especially when the pattern meets the roads (Fig. 13a). This is due to the irregularity exerted by the roads. More regular roads cause more indeterminacy (Fig. 13b). More complex roads make faster emergence of determinacy happen in the model (Fig. 13c).

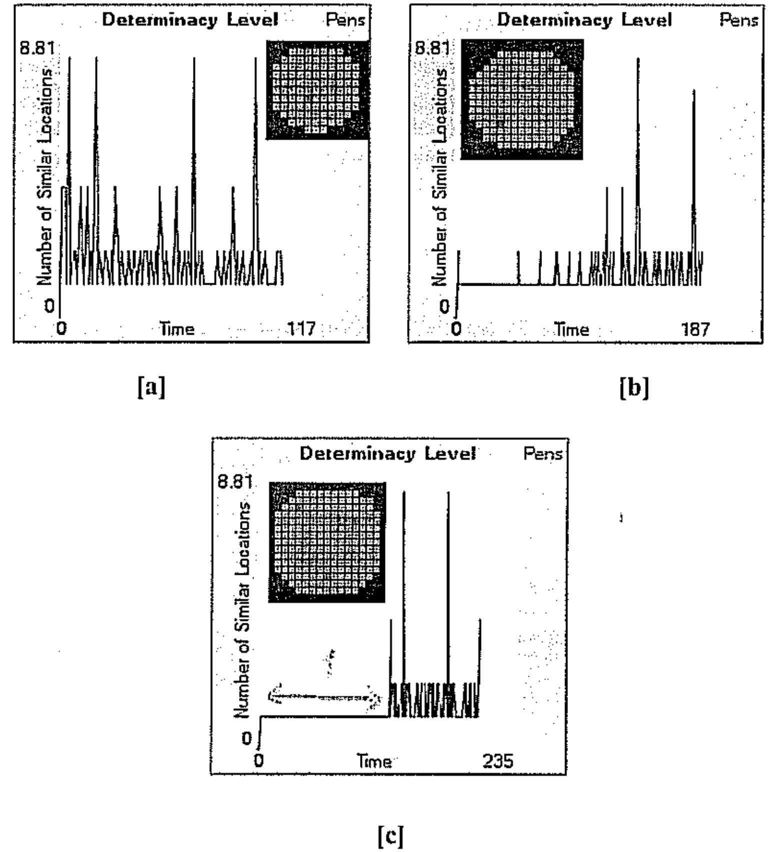
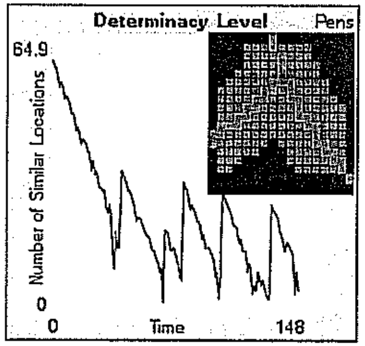
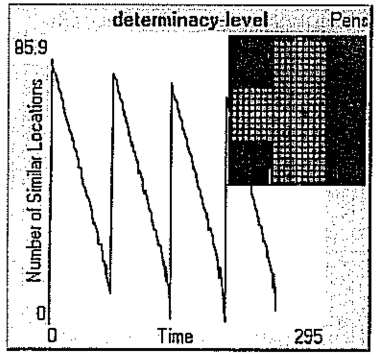


Fig. 10. Model determinacy just using the *Distance-to-Gravity-Center* rule. **[a]** Using one seed causes indeterminacy from the start and it continues. **[b]** Using two separate seeds reduces the indeterminacy until the pattern includes both the seeds. **[c]** With three separate seeds, simulation starts without indeterminacy and continues until the pattern includes all the seeds.

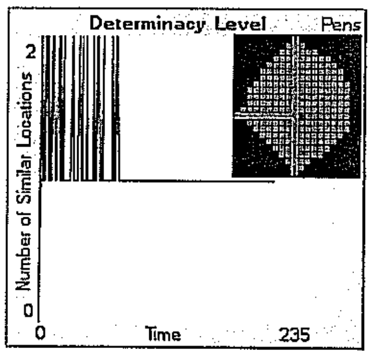


[a]

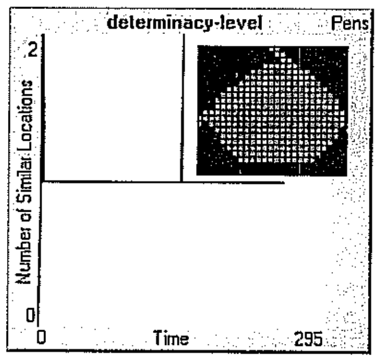


[b]

Fig. 11. Model determinacy just using the *Distance-to-Road* rule causes **[a]** high indeterminacy which is represented as jagged rise and fall of the determinacy level **[b]** even when the roads are regular and simple.

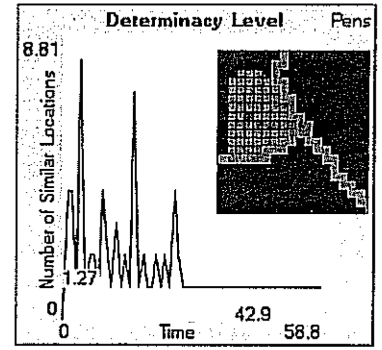


[a]

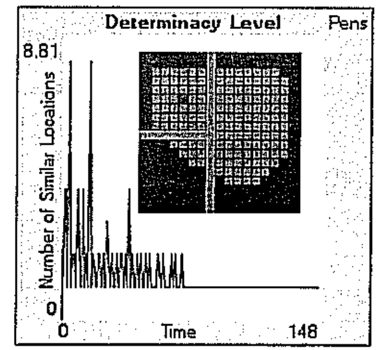


[b]

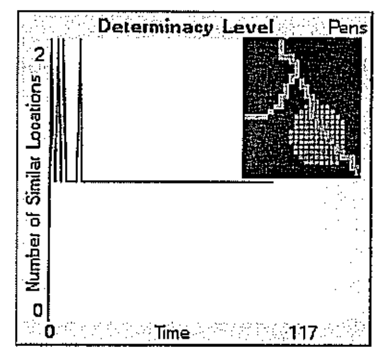
Fig. 12. Model determinacy rises using the *Distance-to-Road* rule and the *Distance-to-Road* rule together. **[a]** Using regular roads, determinacy varies between 2 and 3 possible locations. **[b]** Using irregular roads improves determinacy as 3 ties rarely happen.



[a]



[b]



[c]

Fig. 13. Model determinacy adding the *Distance-to-Road* rule, when having **[a]** Irregular simple roads, **[b]** Regular roads, or **[c]** Irregular complex roads.

5.2 Local Rules

Adding the free spaces increases the irregularity in the generated patterns and reduces the indeterminacy of the simulation model. The simulations carried out for different combination of rules and initial states (arrangement of seeds and geometry of roads) shows that still minor indeterminacy is possible, especially at first iterations when a few buildings still exists in the environment (Fig. 14). As the simulation goes on, the indeterminacy disappears. Combining the defined global and local rules, we did not observe any indeterminacy after 30 iterations.

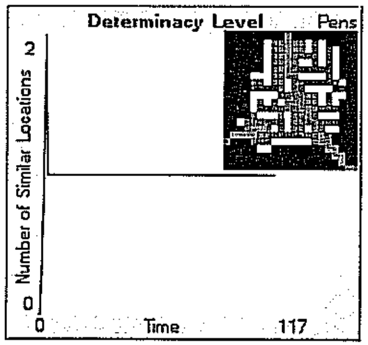


Fig. 14. Model determinacy combining the defined global and local rules. It shows some random peeks at the beginning of the simulation, when few buildings still exist in the space. Repeating the simulation with different arrangements of seeds and different geometry of roads, the number of similar locations remains under 2 locations.

6 Numerical Evaluation of the Small-World Network Pattern Emergence in the Model

Fig. 15 shows the small-world network characteristics as a semi-logarithmic graph (Fig. 2) generated, using the rewiring approach introduced by Watts and Strogatz (1998) in section 2, with 4 degrees at 0.01 intervals. We selected 4 degrees for the small-world network to enable each node to become a cross intersection that are typical in urban structures. The 0.01 interval is selected arbitrarily. It affects our comparison precision as we derive the nearest value of p on x-axis separated at 0.01 intervals (Table 1).

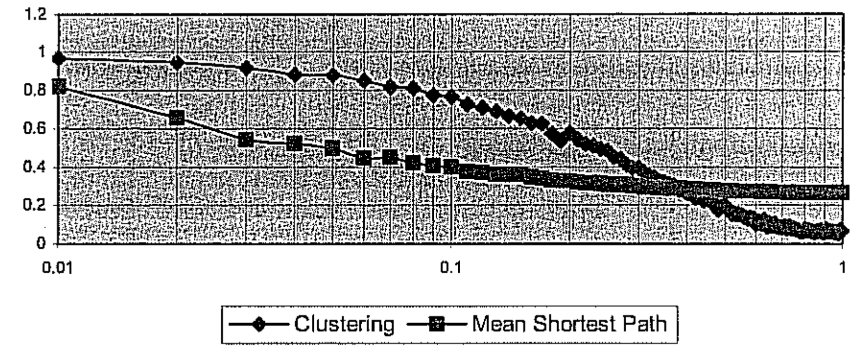


Fig. 15. Characteristics of the small-world Network for 100 nodes with 4 degrees at 0.01 intervals. The Maximum differences between the clustering coefficient and the mean-shortest path length, ranges from 0.37 to 0.40, happens between p=0.03 and p=0.09. The value for p=0 is dropped because of using logarithmic scale in x axis.

Table 1 lists different rule-sets used to generate the patterns. We executed the simulation for each rule-set, considering different (about 10) arrangement of seeds (single, multiple, attached, and detached) and different geometry of roads (regular and irregular). Then the averages of the following values are calculated (Table 1):

- the clustering coefficient,
- the mean-shortest path length,
- $P_{(clustering\ coefficient)}$ and $P_{(mean\text{-}shortest\ path\ length)}$ that are derived from the graph showed in Fig. 15, represent the corresponding probability value of the small-world networks that produce the simulated clustering coefficient and the mean-shortest path length values,
- D_p as the absolute difference between $P_{(clustering\ coefficient)}$ and $P_{(mean\text{-}shortest\ path\ length)}$, and
- PLE_{mean} and PLE_{Std} which represent mean and standard deviation of the power-law distribution exponent fitted to the degree distribution of the simulation.

Table 1. Emergence of the small-world network pattern in the simulation model.

Rules Set	Roads Exists?	Distance-to-Road	Share-Free-Space	Adjoining-Free-Space	Access-Space	Adjoining-Access-Space	Sun-Position	Clustering Coefficient	Mean-Shortest Path Length	$P_{clustering\ coefficient}$	$P_{mean\text{-}shortest\ path\ length}$	Dp	PLE_{mean}	PLE_{Std}
1							✓	0.485	0.638	0.260	0.030	0.230	-2.237	0.621
2			✓	✓				0.586	0.764	0.187	0.019	0.169	-3.042	0.564
3				✓			✓	0.678	0.642	0.143	0.027	0.117	-1.361	0.342
4			✓	✓			✓	0.496	0.810	0.240	0.015	0.225	-2.726	0.468
5				✓				0.777	0.523	0.100	0.045	0.055	-1.870	0.485
6			✓	✓				0.594	0.841	0.180	0.015	0.165	-3.066	0.591
7	✓			✓			✓	0.791	0.474	0.090	0.065	0.025	-2.109	0.427
8	✓			✓				0.882	0.488	0.050	0.060	0.030	-2.360	0.296
9	✓	✓		✓				0.772	0.393	0.103	0.103	0.007	-1.484	0.830
10	✓	✓		✓			✓	0.781	0.428	0.090	0.090	0.030	-1.055	0.847
11	✓	✓		✓	✓		✓	0.874	0.502	0.050	0.050	0.000	-1.497	0.538
12	✓	✓		✓	✓	✓		0.894	0.457	0.045	0.060	0.015	-1.772	0.521
13	✓	✓		✓	✓	✓	✓	0.847	0.463	0.065	0.060	0.005	-2.038	0.472

The *Distance-to-Center-of-Gravity* and *Free-Space* rules are set on by default.
The values are averages of the results of the simulations carried out for each of the rule-sets. Then D_p might not be exactly equal absolute difference of $P_{(clustering\ coefficient)}$ and $P_{(mean\text{-}shortest\ path\ length)}$.
Small D_p and PLE_{Std} represent emergence of a valid and stable the small-world network pattern that we expect for a city. Large D_p shows that the simulated pattern does not refer to unique small-world network.
Large PLE_{Std} represents instability of values calculated for the generated small-world network.

Then the main results are as follow:

- The rule-sets 9 to 13 assert the discussions in section 2 that existence of a few roads (long links) among a large amount of pedestrian passages (short links) have significant effect in emergence of small-world networks. This effect is visible, even when the *Distance-to-Road* rule is off (rule-sets 7 and 8). The *Distance-to-Road* rule improves the small-world network pattern more.
- The *Share-Free-Space* rule damages the small-world network pattern (rule-sets 2, 4, 6, and 14). Combination of the *Adjoining-Access-Space* rule and the *Sun-Position* rule has generative effects (rule-sets 1, 3, and 5).
- The p value of the results with low D_p and PLE_{Std}, like the rule-sets 10 and 13, ranges from 0.05 to 0.09 that approximately fits in the range of the maximum differences between the clustering coefficient and the mean-shortest path length which happens between p=0.03 and p=0.09 (Fig. 15). The rule-sets 10 and 13 also have similar PLE_{Std} equals 0.472 and quite similar PLE_{mean} around -2.0.

7 Conclusions

We propose that the values of the rule-sets 10 and 13 (Table 1) represent the characteristics of not pre-planned cities, or more properly organic cities, settled on flat areas (no topography effect). Consider that the rules and the rule-sets introduced here are just one possible alternative to describe the studied urban patterns.

Investigation of the small-world network pattern provides us a basis to study emergence of other urban patterns like Zipf's law distribution of length of the passages (Carvalho and Penn, 2004) and fractal patterns. The rule-sets 10 and 13 (Table 1) are the first candidates to derive these patterns.

We are still using a random generator to define location of the buildings. The introduction of new entities, rules, and attributes from the physical reality, like topography and access to natural resources, will reduce the indeterminacy (the number of ties) in the simulation model. We might be able to omit the random generator.

Our numerical evaluation showed that D_p remains under 0.1 when roads exists in the simulation model (Table 1). It seems that following spatial rules derived from the physical reality, it is difficult to avoid emergence of the small-world network pattern. This observation restates the criticism made by urbanists like Alexander and Salingaros against our contemporary cities which their effective small-world network patterns are damaged. They say that people have to be educated to behave against the archetypes and create such unconnected (not so alive) cities. They refer to defectiveness of our modern (20th century) urban architecture and design educations and plans made by governments. The problem is that economical and political issues and top-down design approach have dominated our urban design. It dismisses or underestimates the spatial rules (especially local rules) that generate urban patterns.

Urban designers can enrich their top-down global viewpoints on patterns with detailed bottom-up regeneration of those patterns. This also helps to raise questions like how much information exists in urban patterns. For example, we can count rules or measure the length of the program generated the pattern. We used 8 rules here that are programmed in less than 100 lines. An expected result would be that our urban design approaches not only dismissed some important (spatial) rules, but also carries a large amount of redundancies[12]. This knowledge can help to design better cities and improve the quality of life in the existent cities.

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