Network Analysis of Emergent Spatial Structure in Cities

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***Abstract*— This paper employs multi-agent simulations to examine patterns of collective behaviour in the formation of cities. It explores a simple preferential model which addresses the link between group formation and spatial arrangements. Nodes represent urban artifact formed by groups sharing attributes and links represent connection paths among entities. The urban artifacts connect together in the model to form "cities". Although the model did not contain sufficient spatial structuring, the resulting network displayed some characteristics that would be expected in real cities. It had a central core or transit elements, had a realistic density of connections, and appeared to display power law behaviour.**

***Index Terms*— Complexity, cities, agent-based models, networks, power law distribution.**

I. Introduction

It has been demonstrated in the context of multi-agent simulations studying patterns of collective behaviour, that preferential bias in group dynamics is an instance of a universality class of behaviours.

Universality pertains to the notion of parameter relevance and the idea that many conceptually different systems can be described equivalently, irrespective of the finer details of each model. This is especially true for model that exhibit scale-free behaviour which is generally indicated by the existence of a power law.

It has recently been recognised that cities evolve in bottom-up fashion following well-defined scaling laws with a high degree of self-similarity. Thus, models of preferential attachment, segregation and self-reinforcement have been applied to study the evolution of cities arguing for a strong relationship between social formations and the spatial arrangement they engender.

We explore a simple preferential model which addresses in an indirect manner, the link between group formation and spatial arrangement, to simulate the emergence of city structures.

In our adopted network paradigm, a node represents an urban artifact, for example, an educational establishment (i.e. a school), an industrial establishment (shops), transportation infrastructures (roads) etc.

These nodes indirectly represent groups of people sharing those attributes, needs or properties that would give rise to corresponding artifacts: for example, a religious group may establish a church.

Such indirect relation is realised by the way nodes (i.e. urban artifacts) connect together in the model to form "cities". We adopt the notion of preferential attachment so that nodes injected into the running simulation tend to connect to preferred nodes; preference pertains to a set of simple heuristics attributable to the nature of the group identified by a given artifact.

We analyse the resulting "cities" using modern network analysis tools to detect whether our model displays the scale-free behaviour reported in the literature. We also qualitatively compare the resulting structures (in terms of distribution of and links between artifact types) with real world cities in order to see the extent of its applicability.

The present investigation may be particularly relevant in the context of city planning and design that takes into account "organic", bottom-up growth, evolving out of the relation between group formations and spatial arrangements.

II. Background

There is a growing body of work that is developing an integrated theory with regard to how cities evolve and develop. Cities are no longer being regarded as disordered systems but rather a form of urban complexity that has its basis in the regular ordering of size and shape across many spatial scales.

This integrated theory of how cities evolve, links urban economics and transportation behavior to developments in network science, allometric growth, and fractal geometry [1]. By applying this methodology it can provide insights into the resource limits facing cities in terms of density, compactness, and sprawl, and related questions of sustainability. Batty states that this methodology “has the potential to enrich current approaches to city planning and replace traditional top-down strategies with realistic city plans that benefit all city dwellers.”As cities grow in size, physical networks tend to grow more slowly than city size; that is the physical infrastructure used to move resources around does not increase as fast as the number of such resources, whereas key economic activities increase faster than city size in terms of population (Batty [1] quoting West [2]).

Space can be used both in a conservative mode to structure and reproduce existing social relations and in a generative mode to create the potential for new relations by using space to create co-presence through integration [3]. The configuration of the urban street network is a key determinant of movement flows in a city. Hillier describes this as the theory of “natural movement” [4]. The spatial syntax analysis seeks to combine the physical and socio-economic behavior and attempts to explain the reason for the system to behave in this way. Ideally this would be illustrated by defining the behaviour of the system at a micro level, while at a macro level the the spatial patterns can be brought into clear view. Vaughan argues that spatial syntax models are applicable in design as they are explanatory in themselves [3].

The second idea is that human space is not just about the properties of individual spaces, but about the inter- relations between the many spaces that make up the spatial layout of a building or a city [3].

> "These least line axial maps turned out to have some remarkable properties. First they turned out to have a fractal nature (Carvalho and Penn 2004), in that all urban street networks, from Shiraz to Chicago, at whatever urban scale we consider them, are made up of a very small number of long lines and a very large number of small lines. Second by simply applying the integration and choice measures to the least line map and correlating the spatial values with observed movement rates, we commonly found that somewhere between 60% and 80% of the differences in movement flows along lines could be accounted for in terms of the configuration of the grid itself (see Hillier 1989, Hillier and Penn 1996 and etc.) "

A comprehensive criticism of space syntax was developed by Ratti [5]. He argues that it is incorrect to view the city from an entirely topological perspective, disregarding geographical information. In addition, an axial map removes all 3D information and assumes that the urban grid is loaded with buildings in a uniform way. However some of the shortcomings that Ratti identifies could be addressed by more complex models that incorporate digitized urban data from a variety of sources.

III. Methods

We proposed to illustrate the behavior of the development of a city based on some micro-scale rules that would explain the macro-scale outcomes. It was initially thought that this model could be compared to the development of an existing city. However due to the difficulty in identifying a micro-scale rule that was valid in a short time period, it was decided that an illustration of the principle would suffice, with further refinement of the rules planned in the future.

Six categories were identified as random nodes that entered into the system at each time step. Each node could connect to another node based on a probability. The nodes that can attach to other nodes are listed as follows:

- Road --> All
- Industry --> Road, Industry, Resources, Commercial
- Education --> Education, Residences, Roads
- Residences --> Roads, Residences, Resources, Education
- Resources --> Resources, Roads, Industry, Education

For nodes that can connect to each other, a weighted probability was assigned to each node so that they had a higher preference.

Our simulation was created using Mathematica 6.0 and the associated Combinatorica package to allow for proper network analysis. In the beginning of the simulation, a seed node is created which takes on one of the six possible identities previously mentioned. The node identity is selected based upon a weighted probability distribution: road (25%), industry (10%), education (10%), house (18%), resource (21%) and commercial (14%). Subsequent nodes are created one-by-one in the same fashion and, immediately after they are created, form one connection to a random node in the network of a compatible type (using the previously defined compatibility relationships). This creation and connection process is repeated for an arbitrary number of nodes. When network construction is complete, its structure is displayed using spring embedding. Aside from improving the aesthetic appearance of the network, spring embedding “pulls” clusters of more highly connected nodes away from the rest of the network so they become more visually apparent. Each node's type can be identified by a distinct color: roads are black, houses are blue, industries are yellow, educational institutions are red, resources are green and commercial markets are pink. Combinatorica's built-in tools were used to determine metrics such as average degree, variance, degree density scale-free behavior.

IV. Results

This system demonstrates patterns like those that appear in cities. It has a denser core and a periphery of les connected elements. Industry is connected to resources and often connects in a chain in toward the core. There appear to be clustering of houses that are similar to neighbourhoods. The roads also form a kind of central chain that looks like a transportation route in a real city. The resources seem to be among the least connected elements. This would be fairly common due to low energy costs.

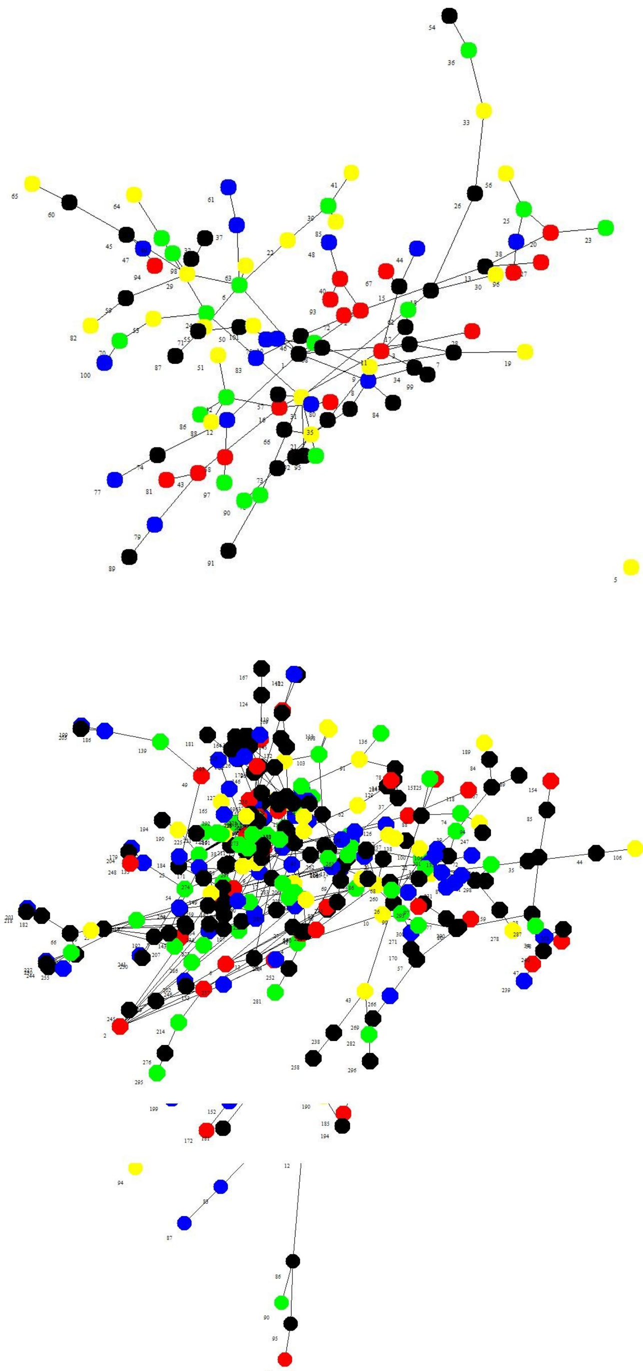
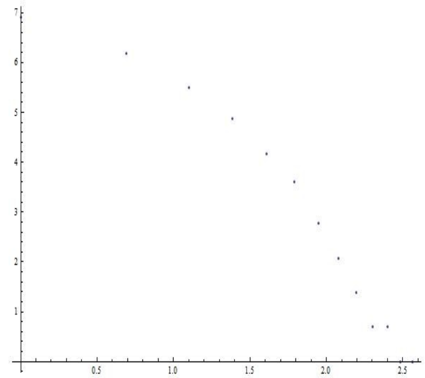


Figure 1: Resulting networks with 200 and 300 nodes respectively.

One weakness in the model is that there can be roads that don't go anywhere. In a real system there would be no incentive to build these roads. One flaw in the model is that rules do not establish those structural relations. As a result, the roads are not required to carry anything and they are not required to go anywhere.



{{0., 6.90875}, {0.693147, 6.18826}, {1.09861, 5.50533}, {1.38629, 4.86753}, {1.60944, 4.17439}, {1.79176, 3.61092}, {1.94591, 2.77259}, {2.07944, 2.07944}, {2.19722, 1.38629}, {2.30259, 0.693147}, {2.3979, 0.693147}, {2.48491, 0.}, {2.56495, 0.}}

Figure 2: Cumulative distribution with respect to the degree of nodes.

Some metrics were evaluated and as expected it indeed reflects those of a real network. The densities of several 1000 node networks were calculated and found to be of the order 0.0001. The shows the behavior of the cumulative distribution function with respect to the degrees of nodes. After fitting a straight line to the above curve, it was observed that the slope lies between 2 and 3 in all test cases which provides evidence of the existence of a power law - based behavior. An attempt to analyze the clustering co-efficient was fettered by Mathematica's network package. It was decided to use other languages like Python to pursue more analysis but due to time constraints it was procrastinated. It was observed that there certainly lies a large potential for interesting analysis.

V. Conclusion

We applied an indirect strategy to derive the structure of spatial arrangement at city scale from the collective, preferential behaviour of social groups. Groups are made equivalent to urban artifacts the nature of which reflects the need and nature of the group. Each group/artifact is distinguished by a set of preferential heuristics and network structures are generated from the interplay of these rules when artifacts are represented as nodes. We calculated the cluster coefficient for several of the generated networks to confirm that indeed the scale-free behaviour observed in real cities is retained. A qualitative analysis was also performed pertaining to the realistic distribution of artifacts within the boundaries of a city.

Acknowledgement

The authors thank The New England Complex Systems Institute (NECSI) for support in developing models to for this paper.

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