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Procedural urban modeling of population, road network and land use

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Abstract

This paper introduces an urban simulation system generating urban layouts with population, road network and land use layers. The desired urban spatial structure is obtained by generating population map based on population density models. The road network is generated at three spatial levels corresponding to the road hierarchy. The land use allocation is based on rule-based algorithm. And global and local parameters are designed to guarantee the flexibility and modification of urban layouts. The expected results are urban layouts suitable for academic scenario analysis.

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Keywords: procedural modeling; urban modeling; population density; road network; land use

1. Introduction

Procedural modeling has a history of decades, and it was introduced into urban simulation at early this century (Parish and Müller, 2001). Many algorithms are developed since then to simulate buildings, road network and land use. In some literature the authors acknowledged that their work was chiefly motivated by entertainment, such as computer games (Aliaga et al., 2008; Beneš et al., 2014; Lechner et al., 2003; Parish and Müller, 2001; Weber et al., 2009). This motivation led to plausible urban layouts and three-dimensional geometry of urban environments. However the existed models have problems if they are applied in academic fields.

For example, a research of land use impacts on traffic using scenario analysis method, will need simulation data instead of real data to get desired scenarios. To generate the simulation data, an urban layout simulation model

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combined with a traffic simulation model is needed. And such an urban layout simulation model should satisfy the following two important conditions.

The most important is to generate desired urban layouts, including desired urban spatial structure, road network, and land use, so users should have a full control of the model to ensure the desired output. In the urban spatial structure, some existed procedural urban models don't take population into account(Aliaga et al., 2008; Beneš et al., 2014; Weber et al., 2009), and other ones use real data as input. Of course real population data is not hard to obtain today, but it cannot promise a desired urban spatial structure, and users have limited control of real data. As for the road network, it can be generated by a variety of methods which can be basically classified into static and dynamic methods. The dynamic methods generate road networks from several growing points and during some growing periods(Beneš et al., 2014; Lechner et al., 2003; Weber et al., 2009), so it is hard to precisely control the final results. The static methods generate road networks at one go, which is relatively easily to control, but the existed algorithms still do not meet the requirement. For example, in the L-system, highways connect population centers(Parish and Müller, 2001), then the road network is mainly determined by the population density map. In the example-based algorithm, the streets and blocks are mainly influenced by the input urban images(Aliaga et al., 2008). And in the tensor fields, before generating road network, a tensor field should be drawn and modified(Chen et al., 2008), which is an abstract process and is not easy to precisely control. The land use allocation algorithms, however, can basically get desired results(Lechner et al., 2006, 2004; Weber et al., 2009).

Another important thing is flexibility. It is well considered in most procedural road network models which provide easy ways for users to modify the simulation results. But in the field of land use, some requirements are not met. For example, in the scenario analysis mentioned above, the users may need to change land use proportion in some districts or neighborhoods, such as from 80% residence and 20% retail to 60% residence, 30% retail and 10% open space, and they should not have to change the land use of lots and parcels one by one. Such kind of flexibility is not achieved yet.

In this paper, we introduce an urban simulation system motivated by academic research. The system will generate population layer, traffic infrastructure layer, and land use layer. In section 2 we introduce the basic concepts and the pipeline of our system, and then the generation of population density, road network and land use are described in section 3, 4 and 5 separately. Finally the expected results are shown and discussed in section 6.

2. Overview

2.1. Definitions

Our city generation model consists of three basic layers: population, land use, and infrastructure. At this stage, the layer of infrastructure has only road network. The road network and land use are both hierarchical layers based on city regions and road network system.

The road network in our system, in accordance with the widely used road hierarchy (Lay, 2009; Marshall, 2005), consists of the *highway*, *arterial*, *distributor (district and local)*, and *local access*. Accordingly, in our definition, a *city* is divided into *districts*, and a district into *neighborhoods*, then into *lots*. The district is an area surrounded by highways and arterials, and the neighborhood is surrounded by distributors, and the lot is surrounded by local accesses. Finally, at this stage we consider a set of five land uses: the *residential*, the *industrial*, the *office*, the *retail and services*, and the *park and open space*.

2.2. Pipeline

Fig. 1 shows the pipeline of our system. The input to our model includes: the population P, the urban area A, and the desired land use percentages L. Other important parameters, such as the urban spatial structure and the road pattern, are preset, and users can just choose desired values or change them interactively during the modeling procedures.

First, a population density map is created based on the preset population density models. The layer of population density is an input to the generation of road network and land use layers. The two layers consist of three spatial levels. At the city level, the highway and arterial are generated to form a spatial framework of urban layout, and the city is divided into districts at the same time. Then the land uses are allocated to the districts, in the form of a set of percentage values of land use. The district level has similar procedures creating the distributor and the neighborhoods, and also the land use allocation on the neighborhoods. At last is the neighborhood level which produces the local access and the lots, and land use is allocated specifically on the lots.

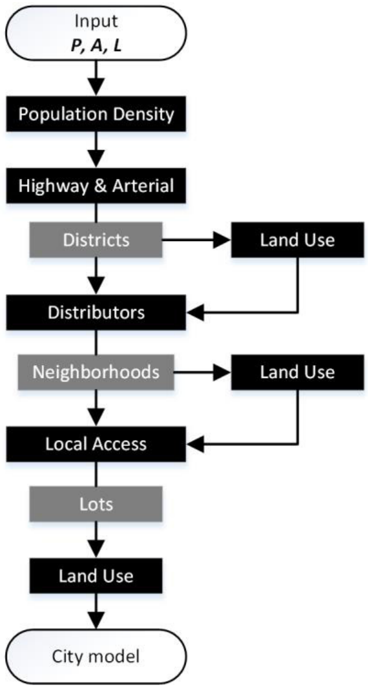

Fig. 1. The pipeline of the city simulation model

The output of this system is a city layout with population, road network and land use. To guarantee sufficient flexibility, users can adjust or regenerate the road network and land use of all districts, neighborhoods and lots, which make it possible to control the whole city and its all parts.

3. Creating the population density map

Of course users can input their own population data from real world. But in order to realize the full control, desired urban spatial structure, and the high flexibility, it is necessary to provide a convenient way for users to draw a population density map.

Firstly, we preset some population density models that users can choose to create most typical spatial distributions of population. These population density models include: the negative exponential function(Clark, 1951), the normal distribution function(Newling, 1969), the cubic spline function(Suits et al., 1978), and so on.

According to the functions, the draft map of population density can be drawn, which is a hypothetical structure that population is evenly distributed at all directions. Thereafter an adjustment process is followed to make it realistic. In this process, some population concentrating directions will be generated either by a random selection process or by users.

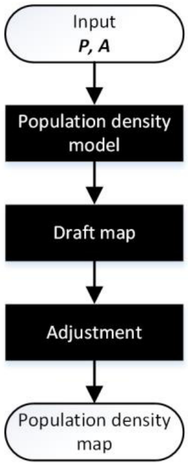

Fig. 2. Population generation

4. Generating the road network

4.1. Basic procedure

The basic parameters for creating a road are *start point*, *segment length*, *direction*, and *end point*. Accordingly the basic road generating procedure has four steps.

First is the generation of the start point. In our system, the start point can only be the city center, or more generally an intersection on of an existed road of the same or higher level in the road hierarchy. The start points of certain level roads controls the density of such road network, so a reasonable distance between two roads and a distance between two intersections must be taken into consideration. The reasonable distance will be found in relative road technology regulations, among a certain value rang(Xu and Huang, 2007).

Similarly, the segment length of a road should be the same as the reasonable distance between two roads of a certain level. And land use will influence the value. For example, the road distance tends to be smaller in residential areas but larger in industrial areas.

The direction of a high-level road, such as a highway or an arterial, is determined by the preset urban form, or tries to connect centers of population (Parish and Müller, 2001). And a low-level road mainly follows the parallel or vertical direction of upper level roads.

A road grows with a segment length every time, generating a new node (the end of the segment), till the node is judged as an end point: (1) the node is outside the urban area; (2) the node is near an upper level road which should not be crossed, for example, a local access should not go across an highway; (3) the node is near an intersection. Then the segment is adapted to the environment in the similar way of Weber et al. (2009).

4.2. Generating the highway

As shown in Fig. 3, users should decide whether to build the highways at first, because the highway network is usually built in big cities, but it is not must-have. If users do not want to build it, the model will jump to the arterial part.

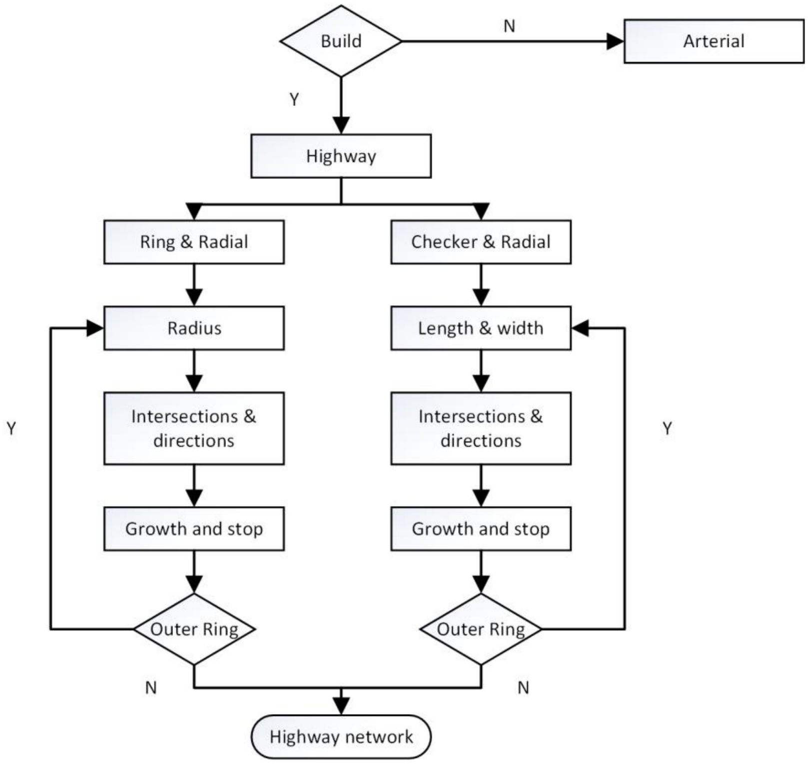

Fig. 3. Highway generation

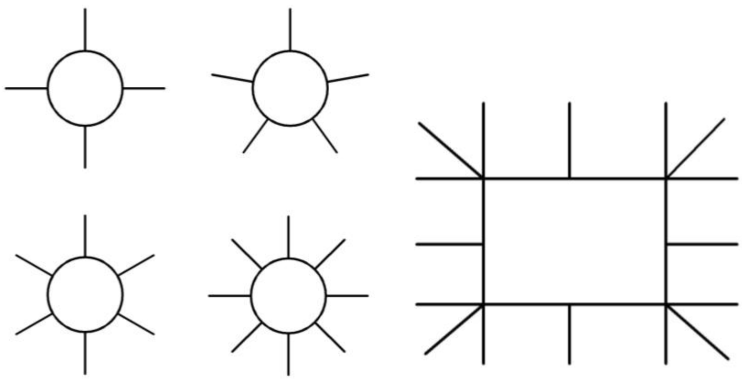

Fig. 4. Highway patterns of ring & radial (left) and checker & radial (right)

The highway network has a close connection with urban form, or it is a part of the urban form. So we preset several popular urban forms with related highway networks. In this paper we discuss two patterns of networks named *ring & radial* and *checker & radial*.

One thing the two networks have in common is that they have at least one ring road. We preset the radius of the 1^{st} ring (in some cities they are called the 2^{nd} ring) in a range between 4 and 5 km, after studied cases of European and Chinese cities. We also found in the case study that the 1^{st} ring usually connects to 6 or 7 other highways, so in our system we preset 4 to 8 intersections (also the start points of radial highways) on the 1^{st} ring road.

The start points and directions of radial highways are easy to set in the ring & radial pattern, and Fig. 4 (left) shows the basic networks. As for the checker & radial pattern, the start points could be on lines or corners of the rectangular 1st ring. The points on lines have only one specific direction, and the ones on corners have three directions, see Fig. 4 (right).

An outer ring could be built if the inner ring has a large distance to the urban edge, and the radius of the outer ring is 4 to 5 km larger than the inner ring. Also, new start points of radial highways could be set with reasonable distance, for example in a range between 5 and 7 km, to neighboring two existing intersections.

If the distance between the outermost ring and the urban edge is less than a certain value, such as 5 km, no other outer rings will be built. As for the radial highways, they should grow to regional or national highways, but in our case they can stop just outside the urban area.

4.3. Generating the arterial

In this paper we introduce two basic patterns of arterials, the *radial* and the *checker*. (Fig. 5.)

The generation of the checker network begins at a start point located in an area around the central point of the city (Fig. 6.). A horizontal and a vertical arterial grow from the point. Then, along the two roads, with a distance between two arterials (the range is between 1.5 and 3 km), four new start points are set, and then four new roads are generated. So the arterial network expands continuously.

The radial arterials begin to grow from the city center, with 5 or 6 radial directions chosen by the users. Then ring arterials grow with a segment in the range between 1.5 and 3 km. On the outer ring arterials new radial arterials can grow between two existing roads, if the distance in between is too large.

An arterial will stop growing if it reaches the urban edge. Or, if the node of the last segment is near a highway intersection, the arterial will connect to the intersection and then stop growing.

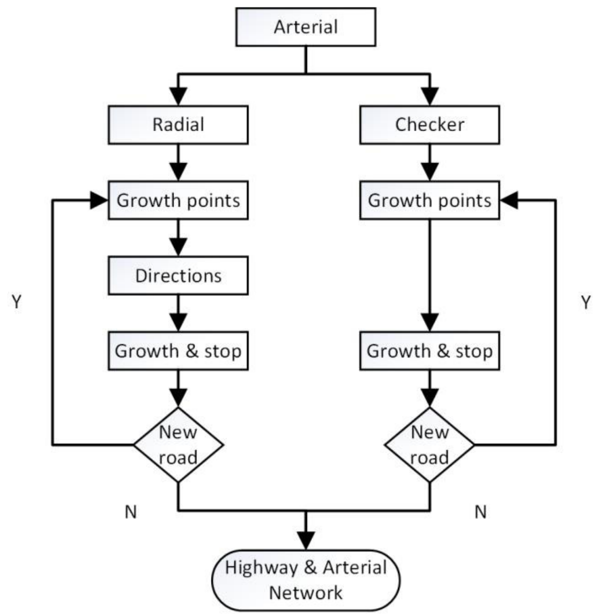

Fig. 5. Arterial generation

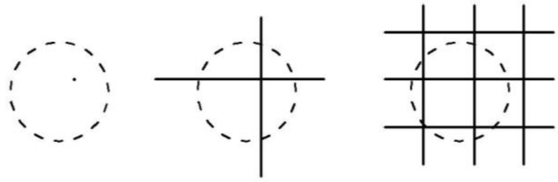

Fig. 6. Generation of checker arterials

4.4. Generating the distributor and local access

The distributor consists of two levels, the district distributor and local distributor. A segment length of the district distributor is about 3 times longer than that of the local distributor; and the district distributor can go across the highway, but the local distributor cannot.

After the generation of highway and arterial network, a city is divided into districts surrounded by existing roads and urban edge. The generation of the distributor network starts at the central district, then outer districts. According to the size of the district and the segment length of the distributor, the start points are distributed on the adjacent two edges of the district. The distributors follow the direction of the arterials or highways nearby, or follow a direction in between the two directions of neighboring two roads.

After the generation of distributors, a district is divided into neighborhoods surrounded by distributors. Then the local access network is generated in each neighborhood. The rest procedures are similar with those of local distributor generation.

5. Allocating the land use

The basic algorithm in our model for allocating land uses is a rule-based one developed from Lechner's work(Lechner et al., 2006). First the allocation rules are set for each land use, and next the amount of each use is calculated according to the urban area and desired land use percentages, and then the uses are allocated one by one.

The land uses are not directly allocated to specific pieces of land, but to district level first, then to neighborhood level and at last to specific lots. It means the land uses will be filled in districts first, according to their allocation rules, with a result of each district like *the residential:70%, the industrial:0%, the office:10%, the retail and services:15%, the park and open space:5%*. Within a district, land uses then will be filled in neighborhoods, with the similar way and results of the district level allocation. Finally within a neighborhood the land uses will occupy their specific lots.

We design such an allocation process for 3 reasons. First, it can balance land use and population at district and neighborhood level, which can provide a more reasonable allocation result. Second, the land use conditions at district and neighborhood level influence the generation of lower road network – it is obvious that a residential district always has a different local road network with an industrial district. Last, in the scenario analysis case mentioned in section 1, the user need systematically change the land use conditions of districts and neighborhoods, so in our model the user can just easily change the total land use percentages of a district instead of the specific land use of many small lots.

6. Results and future work

The output of this system is a city layout with population, road network and land use. Fig. 7 shows some possible results of road network of highways and arterials. The left one is the typical ring & radial pattern, and the right one is the checker & radial pattern.

At this stage of our work, the system is designed to produce general urban layouts. So compared to other work, the results at this stage are more hypothetical rather than plausible. But our proposed model needs less input, fully controls the output, and provides a good flexibility. Also, the results could become much more realistic if some aspects are advanced in the future.

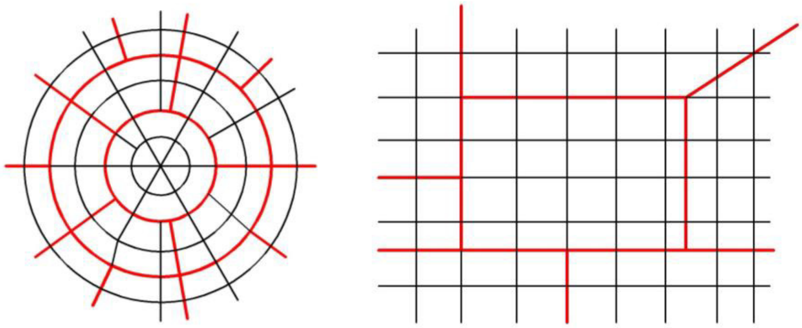

Fig. 7. Road network with highways (red) and arterials (black)

The road pattern which is simple at this stage need to be enriched, so more patterns, such as the *star*, *organic* and *mixed* patterns, will be added. In addition, the road network itself is insufficient for traffic analysis, so some important transport infrastructure, such as bus stations, subway lines, railways and even the airport will be considered. Besides the traffic layer, the land use layer will be improved, for example, taking old town areas or historic districts into account. The natural environment or terrain, which we do not consider at this stage for simulating general urban layouts, will be added to our system to provide a more realistic result.

The procedural urban model is a platform for complex urban study. In next stage, the model will be combined with a traffic simulation model, the supernetwork(Liao, 2013) for example. Then the ultimate combined system, which can generate desired urban layouts and their corresponding traffic data, will be used to systematically analysis the influence of urban land use on traffic.

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