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Procedural modeling of urban layout: population, land use, and road network

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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 a population map based on population density models. The road network is generated at two spatial levels corresponding to the road hierarchy. The land use allocation is based on the *What If?* allocation model. The expected results are urban layouts suitable for academic scenario analysis.

Keywords: procedural modelling; urban simulation; population; land use; road network

1. Introduction

The impact of land use mix on travel behaviour is a traditional research topic, which has recently raised more concern for its influence on energy consumption and exhaust gas emission. Over many years, however, whether land use has a marked impact on travel behaviour is still under debate. For example, in empirical studies on land use mix, an elasticity of vehicle miles travelled (VMT) differs greatly [1]. An important reason is that most studies focused on neighbourhood level land use patterns, but travel behaviour is more influenced by larger spatial level land use patterns [2]. Another reason is that the empirical study is always restricted by data collection. Therefore, a simulation study is designed, aiming to investigate the city & district level land use mix impact on travel behaviour.

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The whole simulation process consists of two parts: one is simulating an urban layout, another is simulating the corresponding traffic. The traffic simulation model must be able to simulate the length, time and mode of trips of a given urban layout. There are many existing travel demand models that can meet this requirement.

The urban layout simulation model must meet two basic requirements. First, it is able to generate desired urban layout. The urban layout includes three aspects: population, road network, and land use. In the aspect of population, some existing urban simulation models don't take population into account [3–5], and others use real data as input. So the existing models cannot generate desired population distribution maps. 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 [4–6], so it is hard to precisely generate a desired result. 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 centres [7], 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 [3]. And in the tensor fields, before generating road network, a tensor field should be drawn and modified [8], which is an abstract process and is not easy to precisely control. Land use allocation algorithms, however, can produce realistic results [5,9,10].

Another requirement is flexibility, which means the simulation results should be easily modified, in order to generate a series of scenarios from one basic urban layout. This requirement is not met by existing urban simulation models especially in land use modification: users must change the land use of lots and parcels one by one.

Therefore, an urban layout model for academic simulation research is needed. In this paper, we introduce such a system. The system will generate a population layer, a road network layer, and a land use layer. In section 2 we introduce the basic concepts and the pipeline of our system, and then the generation of population, road network and land use are described in section 3, 4 and 5 separately. Finally the results are shown and discussed in section 6.

2. Overview

The urban simulation model consists of three basic layers: population, road network, and land use. The road network in our system, in accordance with the widely used road hierarchy [11,12], consists of three levels: highway, arterial and distributor. Accordingly, in our definition, a city is divided into districts which are surrounded by highways and arterials, and a district is divided into neighbourhoods surrounded by distributors. Finally, we consider a set of five land use types: residence, industry, office, commerce, and open & green.

Figure 1 shows the framework of the system. The input to our model includes: the population, the area of the city, and the desired land use percentages. First, the highway and arterial of road network is generated at city level to form a spatial framework of urban layout, and the city is divided into districts at the same time. Next, a draft population density map is created based on population density models. This draft map, which is an input to the land use allocation process, is then adjusted to a final population density map. The land uses are allocated to the districts, in the form of a set of percentages of land uses. After that, the distributor network is generated, which is influenced by the land use condition at district level, and districts are divided into neighbourhoods simultaneously. Similar with the district level, the land use is then allocated at neighbourhood level.

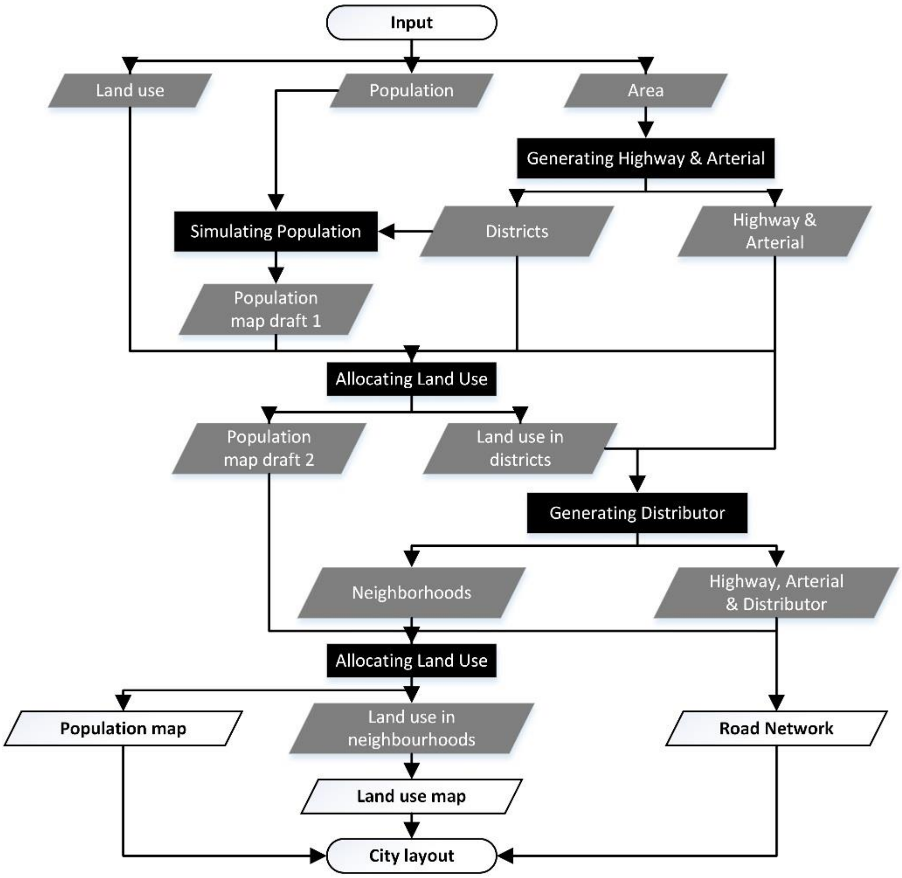

Fig. 1. The framework of the city simulation model.

3. Generating Population

The generation algorithm is based on academic urban population distribution models. A model library is set for users to choose to create most typical spatial distributions of population. At this stage, the model library includes: the negative exponential function [13] and the normal distribution function [14]. More models such as the cubic spline function [15] will be implemented in the future.

With a population density function, a population density map can be easily drawn, but the draft map is a hypothetical structure with a population that is evenly distributed at all directions, see Figure 2 (left). Thereafter an adjustment process combined with the land use allocation process is followed to make it more realistic. This part will be introduced in section 5. The result is that the population is finally adjusted in accordance with distribution of residence land use, see Figure 2 (right).

In the proposed urban simulation system, the users are also allowed to use their own population data of a real city as an alternative input to further generation steps.

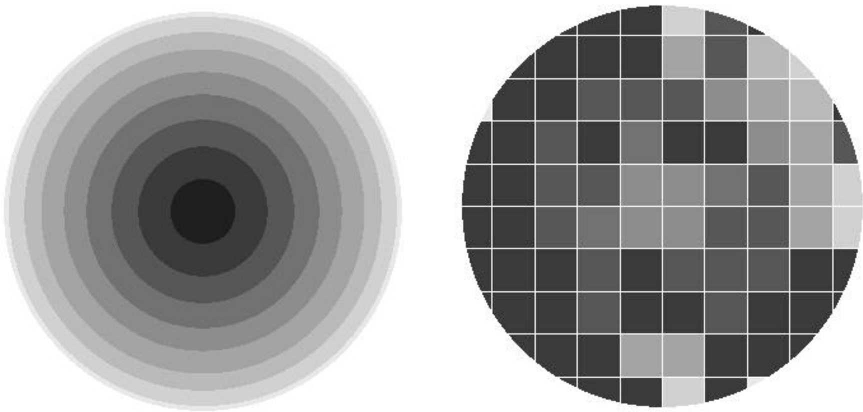

Fig. 2. Population density map generated by negative exponential function. The left is an originally generated map, the right is an adjusted map.

4. Generating Road Network

4.1. Basic procedure

The algorithm of generating road network could be described as pattern-based. A road network pattern library is built, and users just need to pick a desired road pattern form the library. The library currently have two pattern types: radial and checker.

The basic elements for creating a road are start point, segment length, direction, and end point. In our system, the start point can be the city centre, or more generally an intersection on an existed road of the same or higher level. Users can control the distance between two intersections (as well as two parallel roads), which is also the segment length of a road. Land use will also influence the distance. For example, the road distance tends to be smaller in residence areas but larger in industry areas. The direction of a road is determined by the picked pattern.

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 (where population density is zero); (2) the node is near an upper level road which should not be crossed, for example, a distributor should not go across an highway.

4.2. Generating the highway

As shown in Figure 3, users should decide whether to build the highways at first, because a highway network is usually presented in big cities, but it is not compulsory. If users do not want to build it, the model will jump to the arterial part.

We currently collect two typical patterns of highway network in the pattern library - the ring & radial and the checker & radial. The two patterns have in common is that they have at least one ring road and have 4 to 8 intersections (also the start points of radial highways) on the ring road.

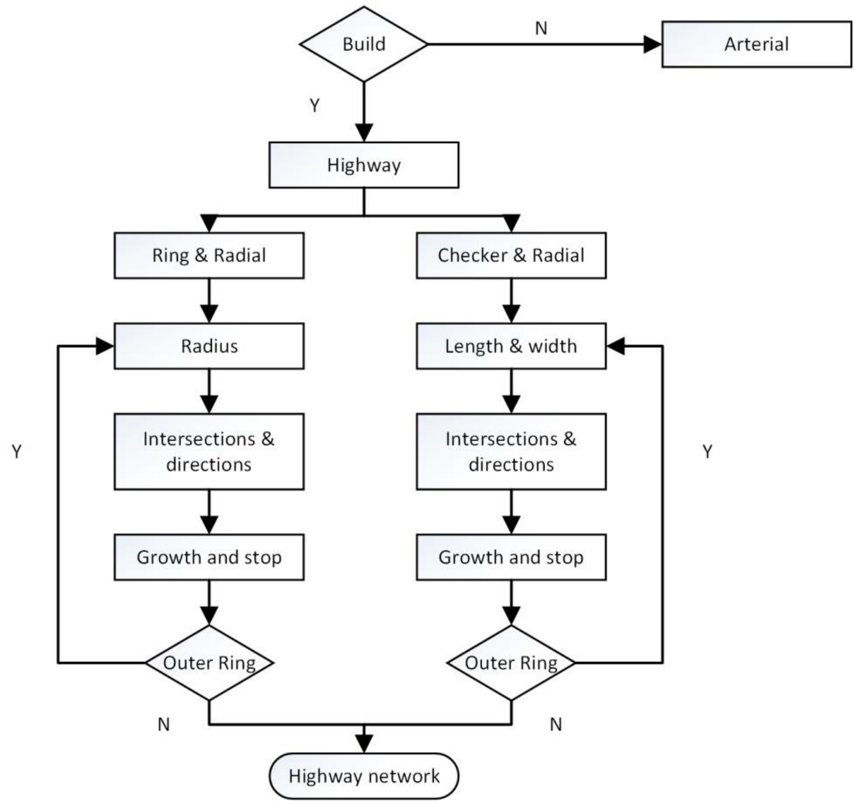

Fig. 3. Highway generation

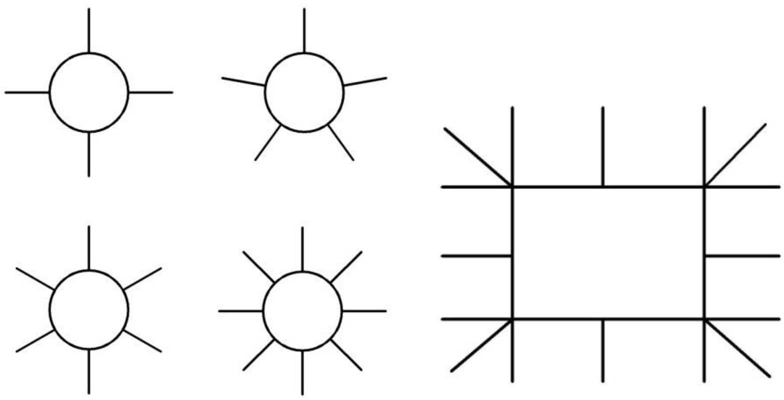

Fig. 4. Highway patterns of ring & radial (left) and checker & radial (right)

The start points and directions of radial highways are easy to set in the ring & radial pattern, and Figure 4 (left) shows the basic networks. As for the checker & radial pattern, the start points could be on lines or corners of the rectangular ring, see Figure 4 (right).

An outer ring could be built if the inner ring has a large distance to the urban edge, and the distance between the two rings is equal to the segment length of highways. Also, new start points of radial highways could be added on the outer ring.

If the distance between the outermost ring and the urban edge is less than the segment length, no other outer rings will be built. As for the radial highways, they should grow to regional or national highways, but in our system they stop just outside the urban area because we focus on the road network in a city.

4.3. Generating the arterial

Similar to the highway network, the arterial network has basic patterns collected in the library. In this paper we introduce two patterns, the radial and the checker, see Figure 5 and 6.

The generation of the checker network begins at the city centre. A horizontal and a vertical arterial grow from the point. Then, along the two roads, with a segment length controlled by users, four new start points are set, and then four new roads are generated. Consequently the arterial network expands continuously.

The radial arterials begin to grow from the city centre, with 4 or 8 radial directions chosen by the users. Then ring arterials grow with the segment length. 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.

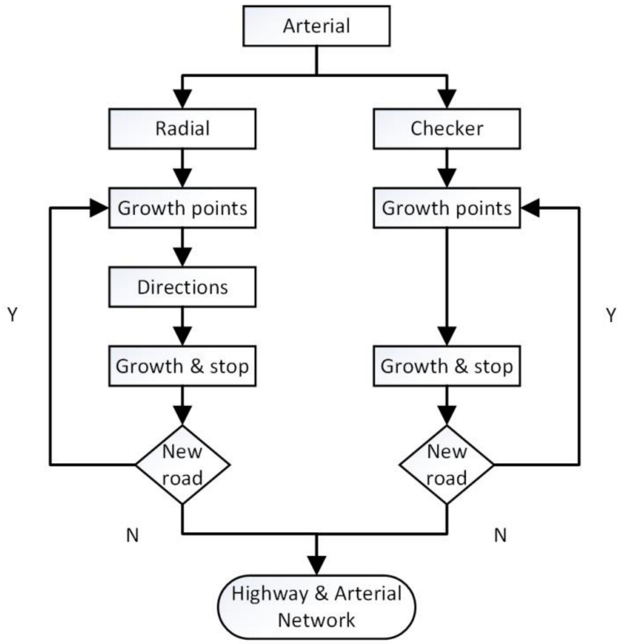

Fig. 5. Arterial generation

4.4. Generating the distributor

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 moving on to the outer districts. The segment length of distributors in a district is influenced by the dominant land use. The districts dominated by industry use prefer a large segment length, while the ones dominated by commerce prefer a short length. 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 neighbouring two roads.

5. Generating Land Use

5.1. Overview

The whole land use generation process consists of three sub-processes: land use allocation in districts, and then in neighbourhoods, and at last in lots. At district level, the input includes the series of land use percentages input by users, as well as the area of the city. The allocation sub-process generates a series of land percentages for each district, for instance, residence: 60%, industry: 10%, office: 10%, commerce: 15%, the open & green: 5%. At neighbourhood level, this series of percentages and the area of a district are the input of the allocation of neighbourhoods within this district, and the output is similar with the district level. At lot level, with similar input, the land use is ultimately allocated to each lot with a specific use.

We design such an allocation process for three reasons. First, it can balance land use and population at district and neighbourhood level, which can provide a more reasonable allocation result. Second, the land use conditions at district and neighbourhood level influence the generation of lower road network – it is obvious that a residence district has a different local road network from an industry district. Last, in the simulation analysis case mentioned in section 1, the users need systematically change the land use conditions of districts and neighbourhoods. In our model the user can easily change the total land use percentages of a district instead of the specific land use of many small lots.

The algorithm of land use allocation is based on *What If?* planning support system [16,17]. The *What If?* model consists of three sub-models: a land-suitability analysis model, a growth-analysis model, and a land-allocation model. In our system the growth-analysis model, which predicts the future demand for land uses, is not needed because the users will input clear land use percentages. Within every land use allocation sub-process there are two steps: suitability analysis and allocation.

5.2. Land-suitability analysis

The suitability of each land unit is calculated using the following equation:

$$S_{ik} = \sum_j w_{kj} r_{ij} \qquad (1)$$

where S_{ik} is the suitability of land unit i for land use k, w_{kj} is the weight of factor j for land use k, and r_{ij} is the rating of land unit i on factor j.

Table 1 provides an example of the factors of suitability at district level, and their ratings. The rating ranges from -2 to 2 which implicates from most unsuitable to most suitable. At this stage only most important factors are considered, and other factors will be added to make the result more realistic. Because all the districts are surrounded by arterials and highways, we only use factor highway to implicate traffic convenience and noise to a district. The factor land value of a district is determined by its location – central districts get the factor type high, fringe districts get the factor type low, and districts in between get the medium. The population is also an important factor. At last, the interactions between land uses must be considered. The factor type local (see Table 1) of a land use means the allocating district has such land use, and the factor type nearby means the district doesn’t have but its adjoined ones have such land use, and the factor type no means no such land use in or around the district. In this paper the value of weight is set as 1, but the value can be adjusted by users in different cases.

Basically, what is expressed through the suitability factors is that residence land use prefers to be away from highways, industry and high land price, but near parks and open space. Commerce land use tends to get close to market (population) and high land value, while office land use has similar preference but contradict busy roads and industry. Industry land use tends to be clustered, and likes land units with low price and population but convenient transportation. Green & open land use tends to get a balanced distribution and prefers low price land units.

Table 1. Default suitability factor weights and ratings of districts.

Factor	Factor Type	Industrial		Residential		Commercial		Official		Open & Green	
		weight	rating	weight	rating	weight	rating	weight	rating	weight	rating
Highway	Entrance	1	1	1	-2	1	0	1	-1	1	0
	Line		0		-2		0		-1		0
	No		0		0		0		0		0
Land value	High	1	-1	1	0	1	2	1	2	1	-1
	Medium		0		1		1		1		0
	Low		1		1		0		0		1
Population	High	1	-2	1	2	1	2	1	2	1	0
	Medium		0		1		1		1		0
	Low		1		0		0		0		0
Industrial	Local	1	--	1	-2	1	0	1	-1	1	1
	Nearby		1		-1		0		0		0
	No		0		0		0		0		0
Residential	Local	1	0	1	--	1	2	1	0	1	1
	Nearby		0		1		1		0		0
	No		0		0		0		0		0
Commercial	Local	1	0	1	1	1	--	1	0	1	0
	Nearby		0		0		0		0		0
	No		0		0		0		0		0
Official	Local	1	0	1	1	1	1	1	--	1	0
	Nearby		0		0		0		1		0
	No		0		0		0		0		0
Green & Open	Local	1	0	1	2	1	1	1	1	1	--
	Nearby		0		1		0		0		0
	No		0		0		0		0		1

5.3. Land use allocation

With the input, the series of land use percentages and the area of upper level land unit, the amount of each use to be allocated can be easily calculated. Other parameters include: land use allocation order, minimum and maximum land unit sizes, and land use controls. Table 2 shows an example of values of these parameters in the districts allocation sub-process.

Before allocating the uses in the allocation order, the least amount of land use, such as the commerce and open & green according to the land use controls in Table 2, should be allocated firstly. At district level, the industry, the commerce, the office, and the open & green uses follow a similar standard allocation algorithm. A land use, according to its result of the suitability analysis, is allocated to any one of the districts with highest suitability (there may be several districts with a same highest suitability). After that, the suitability of the neighbouring districts will be re-evaluated, for the cluster effect of land uses. Next the land use is allocated to any one of the left districts with highest suitability. The last two steps are repeated until all of this land use is allocated. Following the next land use type in the allocation order is to be allocated.

The residence allocation algorithm at district level is a bit different, because it interacts with the population map. After the residence suitability analysis, the draft population map generated directly by population density model is adjusted – people move from districts with lower suitability to districts with higher suitability. According to the updated population map, the residence land is firstly allocated to any one of the districts with highest population density. The allocating principle is to provide just sufficient dwellings for inhabitants in the district. In case the available land for residence in the district is not enough, the exceeded people then move evenly to the surrounding districts which have not yet been allocated, and of course the population map is adjusted as well. Next the residence is allocated to the other districts with highest population density in the remaining districts, until all the residence land is allocated.

Table 2. Default allocation parameters at district level

Land use	Allocation order	Land use controls	Min size (%)	Max size (%)
Industrial	1		5	90
Residential	2		1	90
Commercial	3	At least 5%	5	95
Official	4		1	90
Open & Green	5	At least 5%	5	95

The land use allocation at the neighbourhood level follows the standard allocation algorithm mentioned at district level, with according values.

6. Results and Discussion

The output of this system is a city layout with population, road network and land use. Figure 6 shows two results of road network. The left one is the radial pattern, and the right one is the checker pattern. Figure 7 shows a result of land use.

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 other aspects are advanced in the future.

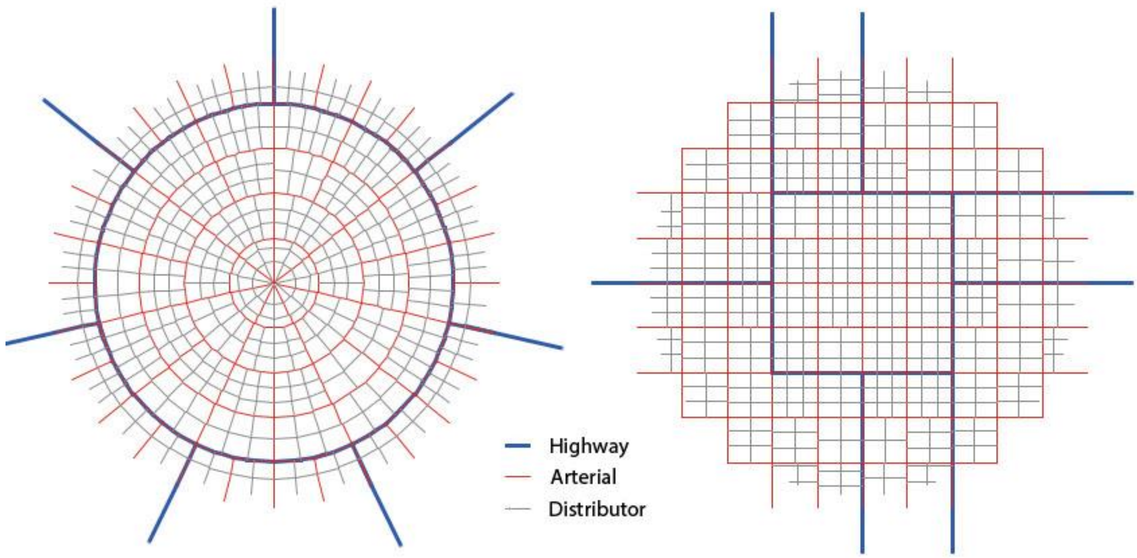

Fig. 6. Examples of road network. Left: radial. Right: checker.

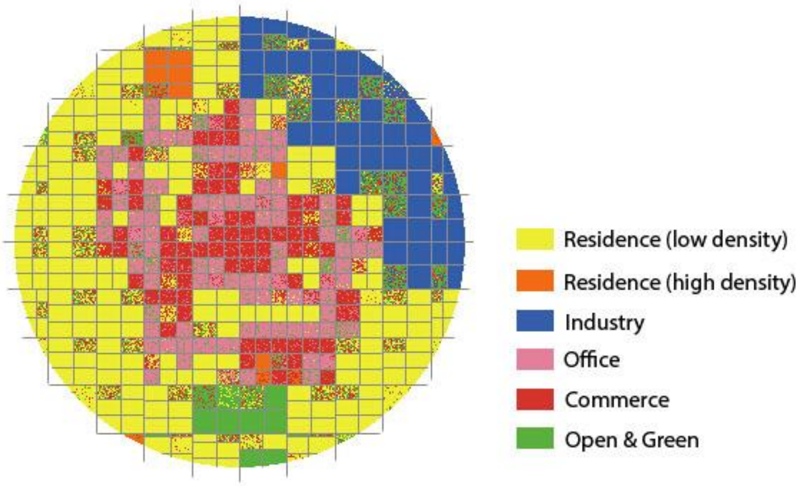

Fig. 7. An example of land use

The road pattern, which is simple at this stage, can be enriched with more patterns such as the star, organic and mixed patterns. In addition, the road network itself is insufficient for traffic analysis, therefore important transport infrastructure, such as bus stations, subway lines, railways and 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 ultimate combined system, which can generate desired urban layouts and their corresponding traffic data, will be used to systematically analyse the influence of urban land use on traffic.

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