

Procedural City Layout Generation Based on Urban Land Use Models

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Abstract

Training and simulation applications in virtual worlds require significant amounts of urban environments. Procedural generation is an efficient way to create such models. Existing approaches for procedural modelling of cities aim at facilitating the work of urban planners and artists, but either require expert knowledge or external input data to generate results that resemble real-life cities, or they have long computation times, and thus are unsuitable for non-experts such as training instructors. We propose a method that procedurally creates layouts of structurally plausible cities from high-level, intuitive user input such as city size, location and historic background. The resulting layouts consist of different kinds of city districts which are arranged using constraints derived from established models of urban land use. Our approach avoids the need for external expert engagement in the creation process, and allows for the generation of large city layouts in seconds, making it significantly faster than comparable agent-based software and thus supporting the needs of non-expert creators of virtual cities for many applications.

Categories and Subject Descriptors (according to ACM CCS): Computer Graphics [I.3.5]: Computational Geometry and Object Modelling—, Simulation and Modelling [I.6.7]: Types of Simulation - Gaming—

1. Introduction and Related Work

Procedural modelling is especially suitable for urban virtual environments, which require a large amount of models and contain many repeating structures. Building those by hand, as is the traditional approach, is tedious work for humans, but fast and easy to generate with procedural methods. What is often lacking in procedurally generated cities is realistic structure, as creation focuses on building and street generation and rather than on believability. Realism must be added by the user and is not inherent in the generation algorithms, requiring expert knowledge or external data such as population density maps or existing city structures [KM06]. This is not suitable in situations where plausible structures are required, such as training and simulation, but where users lack knowledge in modelling believable city layouts.

Parish and Mueller's CityEngine [PM01] can create complex and detailed models of cities, but utilizes numerous input maps and statistical data from real world cities to achieve realism. The software is designed to facilitate the re-creation of existing cities from external data or the placement of build-

ings and roads by users with a city structure in mind, it does not generate structure by itself. Kelly and McCabe's software CityGen [KM07] generates road networks and fills them with three different types of buildings (down-town, suburban or industrial) which are distributed randomly. Statistical data from existing city patterns could be added to create more realistic cityscapes. In the agent-based approach CityBuilder [LRF*04,LRW*06], the generation of land usage for buildings is done via the interaction of a number of agents performing the role of urban developers. Three distinct types of land use are defined: residential, commercial and industrial. A small town layout of limited scale can be generated over a period of approximately 15 minutes not including the generation of building geometry or textures.

Our work aims at a fast and simple generation of believable city layouts without the need for external input data and with an intuitive user interface. Our goal is that users without prior knowledge in architecture or urban planning are able to generate realistic city layouts for use in their applications, e.g. virtual training environments, urban simulations or computer games.

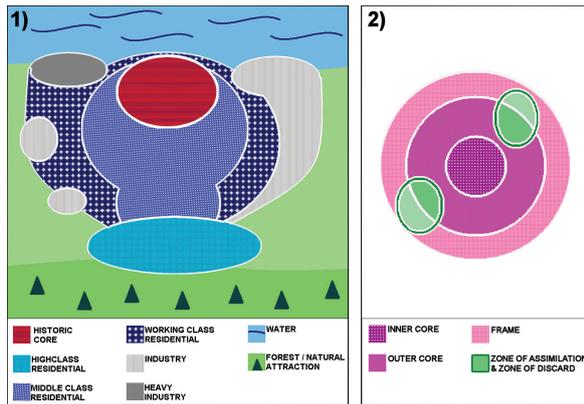


Figure 1: 1) A simple model of the Western European city. 2) Model of the Central Business District.

2. Urban Land Use Models

The identification and explanation of patterns in the urban structure form a major topic in the field of urban geography. In a modern city, different districts are distinguishable by residential and social characteristics (i.e. industry, commerce, high-class and low-class residential areas, etc.). The distribution of those districts within a city is determined by a number of principles of urban land use. Simple generic models divide a city into rings or wedges, while more advanced models take into account different local and historic developments. As a basis for our algorithm, we have focused on land use models for two locations, Western Europe [Ben95, BAB91, Whi84] and North America [Kno94, Cla82, Car95].

The Western European City. Historically, the Western European city is characterized by landmarks such as castles, churches, monumental squares and other symbols of non-economic power. There exists a social and economic gradient from the center to the suburbs, with the wealthier population tending towards the city center. Figure 1.1 shows a general model of a West European city. The old city centers are sharply delineated from surrounding newer areas. Our model supports three different historic city cores:

1. Mercantile historic core: The mercantile city was prevalent in Northern Europe (e.g. the Hanseatic cities). Guilds grouped together all those involved in a particular trade, leading to districts dominated by different trades and little spatial segregation of different classes.
2. Feudal historic core: The feudal city, common in Southern Europe (e.g. Siena and San Gimignano), was a place where feudal families of different factions ruled a city. The (often warring) factions each built their own family palace, housing a noble family, which would dominate the district.
3. Absolutistic historic core: In subjugated cities (e.g. Karl-

sruhe or Stockholm), a single family or individual had the power to rebuild large sections of the city following detailed plans. This led to large-scale geometric structures dominated by the royal palace.

High status districts are located in or close to the city center, especially in Southern Europe. Attractive surroundings can also lead to a high status district in the suburbs. The lower middle class can be found especially in suburban areas in post-war public housing. Some worker districts are in close proximity to the high status districts in the inner city. There is a general tendency for workers towards the periphery.

The North American City. In North America, city landmarks are most often skyscrapers and other symbols of economic power. There exists an anti-urban ethos which is manifested in a drift to the countryside of those who can afford the costs such as longer-distance commuting, leading to a social and economic gradient from the suburbs to the center. The layout of major roads has a big influence on the placement of districts, more so than in European cities. Characteristic for North American cities is the Central Business District (CBD) which makes up the city core. The CBD is the hub of economic, social and political life in the American city. The overall spatial structure of the CBD (Figure 1.2) is dominated by a high density core that contains the retail, office, entertainment and civic zones and a lower density frame with zones of warehousing, hotels, medical and education facilities and manufacturing.

3. Method

This section explains the steps involved in creating a city and the algorithm behind the automatic generation of the layout. Keep in mind that our approach does not intend to model the city growth process but aims at generating only the present state of a city. All parameters and their values are based on the urban land use models described in Section 2.

Generation is a three step process. First, the basic parameters of the city are set, then the districts of the city are generated and lastly their position within the city is determined. The location of the city is marked by designating an area on the terrain. Then the city is configured by setting several parameters. We chose the parameters so that users can easily convey which type of city to generate, as for example:

- city size (as diameter)
- continent on which the city is located (determining the way districts are distributed)
- historical background of the city, usually connected to its location (determining the districts in the core)
- number of highways passing through (influencing the district placement especially in North America)

The appropriate mix of district types in the city is determined based on the parameters. Our model currently includes 18 different district types: 3 residential districts (high class, middle class and working class - drawn in *light to dark blue*

in the output layouts), 2 industry districts (light and heavy industry - grey), 2 commercial districts (green), transportation nodes for humans and for goods (yellow), green spaces and 8 special core districts, e.g. with cathedrals or town squares (other colours).

Once all districts of a city are specified, their location within the city has to be determined. The district placement is influenced by five different factors: type of neighbouring districts (e.g. the high-end residences are unlikely to be situated near an industrial area), terrain type (e.g. industry districts preferring to be near water and highclass residential districts preferring hilly terrain), area of the city (e.g. to represent the social and economic gradient from the center to the suburbs), location of rivers and location of highways. Following the urban land use models, each district type is assigned different values for each of those factors to signify the degree of attraction or repulsion. For an example, the heavy industry districts have a high attraction towards waterside terrain, a high repulsion regarding high-class residential districts but a moderate attraction towards other industry.

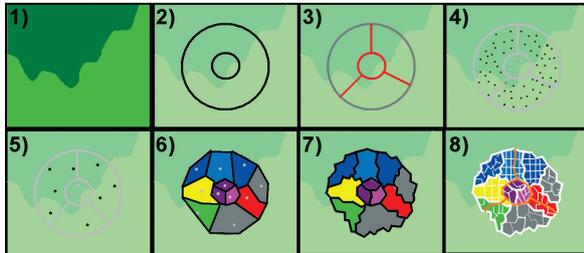


Figure 2: Creation of a City. 1) Terrain 2) City Limits 3) Preliminary Highways 4) Candidate Locations 5) District Locations 6) Voronoi Graph 7) Noise 8) Streets

The district placement algorithm (see below) is based on these attraction and repulsion coefficients. Figure 2 shows the progressive placement of districts in the city. First the city size and location on the terrain are defined by the user (2). The (preliminary) highways are drawn automatically around the core and leading out of the city, possibly towards other cities (3). For the placement of the districts, a number of candidate locations are generated based on a random distribution (4) and the best locations chosen for placement of the districts (5). After the locations of the districts have been determined, a Voronoi diagram is generated from the location points, leading to a polygon shape around each location which describes the district limits in such a way as to equally divide the terrain among the districts (6). Some noise is then added to the diagram to achieve a more realistic look (7) and a street network is generated according to known methods [PM01] (8). We have observed that the optimum number of candidate locations equals approximately twice the number of districts. A higher number of candidate locations does not yield better results.

District placement algorithm. The suitability S of a location l to accommodate a given district d indicates their mutual fitness degree, taking into account the city parameters chosen for that urban land use model. For each district d that has to be allocated, we compute the suitability S of each available candidate location l , and assign to d the location with the highest S . S is a function of five parameters:

- S_d : placement of the district relative to the n other already placed districts
- S_t : terrain type
- S_a : area within the city
- S_r : distance from rivers
- S_h : distance from highways

To give an example, equation 1 shows the calculation of S_d - the suitability of a location regarding the n surrounding already placed districts - , with A_{d_i} being the attraction value towards a type of district d_i , Δ_{d_i} being the distance to d_i and Δ_{min} the minimum possible distance between district centres. Attraction coefficients are assigned integer values between -100 (high repulsion) and 100 (high attraction), which depend on the chosen city type (e.g. European with mercantile core), while distances are measured in pixels.

$$S_d = \sum_{i=1}^n S_{d_i} = \sum_{i=1}^n A_{d_i} * 1 / (\Delta_{d_i} - \Delta_{min}) \quad (1)$$

The values for each parameter are then weighted (w) according to their importance for the city type (e.g. distance from highways plays a greater role in American cities). The final value for S at a candidate location l is then defined as sum of all five values:

$$S = w_d * S_d + w_t * S_t + w_a * S_a + w_r * S_r + w_h * S_h \quad (2)$$

The location l with the highest suitability S for a district d is thus chosen and the district is placed there. This is repeated until all districts have been placed. The procedure is first performed for all the districts of the city core and then for those in the rest of the city. Within both sets, the placement order of the districts is randomized to generate varying output layouts.

4. Results

Figure 3.1 shows a result for a European city with historic core, and Figure 3.2 shows a resulting city layout for a North American city with a CBD. They have visible similarities to the exemplary models (Fig. 1). The European city is a good example for the influence of the terrain: the highclass residential districts (light blue) are found on hilly terrain while the industry (grey) is at the seaside and the city perimeter is shaped by the presence of nearby mountains. The American city shows a discernible influence of the highways, with the industrial (grey) and commercial (green) districts as well as the transportation nodes (yellow) settling close to them, and the residential areas (blue) further away from them.

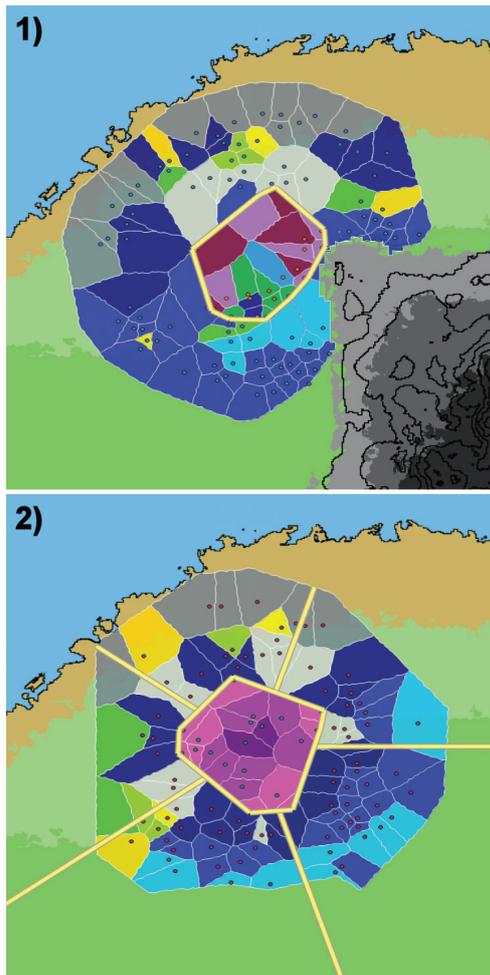


Figure 3: 1) A resulting layout for a Western European city, 2) A resulting layout for a North American city, shown with preliminary highways

To validate our modelling approach, we have consulted experts on urban design and planning. They approved the city models and parameters we use in our algorithm and confirmed the plausibility of the output layouts. Our algorithm efficiently avoids lengthy recursive iterations, yielding plausible output models conforming to scientific models of urban land use. Our system can generate a large city in a few seconds on a modern PC.

5. Conclusion

Our approach generates believable layouts of cities consisting of many different kinds of districts. The generation method is based on models of urban land use, thus requiring neither user knowledge on urban design and planning, nor external input data in order to achieve plausible city layouts.

Several intuitive parameters allow choosing among several different types of cities based for example on their historic background, location, size and shape, covering therefore a large percentage of typical cities in the respective continental settings. Our efficient approach generates layouts in a few seconds, a clear performance distinction from much slower agent-based approaches.

In the future, we would like to extend our algorithm to include more locations (such as cities in Asia and Africa), more lifelike road networks among cities, and a broader choice of districts. Additionally, it would be very interesting to apply our method to generate less common or conventional city designs using different land use models, such as the linear city, garden city or the modernist city. Based on our layouts, street networks and 3D building models can be created using existing techniques for procedural generation. This city generation algorithm is integrated within a prototype modeling framework aimed at procedurally generating virtual worlds, including terrain, vegetation and urban environments [STdKB08]. We believe that such an integrated framework will significantly improve the utility and deployment of training and simulation applications.

This research has been supported by the GATE project, funded by the Netherlands Organization for Scientific Research (NWO) and the Netherlands ICT Research and Innovation Authority (ICT Regie).

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