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EXPLORING URBAN CONFIGURATIONS FOR A WALKABLE NEW TOWN USING EVOLUTIONARY ALGORITHMS

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Abstract. Multi-objective evolutionary algorithms have been successfully applied within various design domains in order to explore the trade-offs between conflicting design criteria. This research investigates how evolutionary algorithms can be used to develop urban configurations for walkable new towns, focusing in particular on the trade-off between travelling time using public transport and accessibility to open space. A population of optimised urban configurations was evolved and analysed, resulting in the identification of three differing typologies for walkable new towns.

Keywords. Urban structure; transportation network; urban density; multi-objective evolutionary algorithms.

1. Introduction

Cities and towns today have outgrown simple ‘hub-and-spoke’ planning typologies to complex and interlinked urban configurations. Developing urban configurations may involve optimizing multiple conflicting performance criteria. In order to facilitate more experimental and at the same time more systematic design explorations, this paper proposes an evolutionary approach to designing an urban configuration for a walkable new town. The walkable new town refers to a town whereby all people can ride public transport to within the neighbourhood of their destinations and then walk to final destinations. The urban configuration refers principally to the urban structure that defines the relationship between transportation networks and land use (Westerman and Austroads, 1998). It involves strategically placing transport nodes in relation to the density of built up areas to make highly accessible activity centres.

The scenario explored in this paper is based on the brief of Vertical Cities Asia Competition 2013 that was organized by National University of Singapore (NUS, 2014). This competition requires high density design proposals for one hundred thousand people on a site with an area of 1 km^2. For this research, the starting point will also be to provide for one hundred thousand people on a 1 km^2 site. However, the focus will be on exploring overall urban configurations for walkable new towns. In particular, the two main performance criteria that are to be explored are: minimization of travel times and maximization of accessibility to open space. In order to further constrain the evolutionary search process, two secondary performance criteria are added: minimization of transport infrastructure cost and minimization of block heights.

Section 2 describes a number of precedents that have applied evolutionary algorithms to evolve urban configurations, section 3 describes the proposed evolutionary exploration method, and section 4 analyses the results and identifies certain key typologies. Finally, section 5 briefly draws conclusions and suggests avenues for future research.

2. Precedents

A number of researchers have applied evolutionary algorithms to urban design to explore different paradigms.

Balling et al (1999) used evolutionary algorithms to design a future land-use plan for the city of Provo, Utah. The goal was to search for a set of plans that satisfied the housing constraints and were Pareto optimal for evaluation criteria ‘Travel Time’, ‘Cost’, and ‘Change’ by changing the widths of 25 identified major corridors of the city. ‘Travel Time’ was calculated on a model that routed all trips on streets throughout the city. ‘Costs’ were calculated as the cost of the corridor upgrades. ‘Change’ was measured by the product of status quo land value and a degree-of-change factor.

Rakha and Reinhart (2012) presented a new urban analysis workflow that develops street and massing layouts for new neighbourhoods in hilly terrains. It consisted of first subdividing the site up according to terrain and, making street widths offsets and generating massing. Then, the potential walkability of each design was evaluated using "Street Smart" walk score algorithm that computes the shortest path to randomly placed amenities such ‘grocery’, ‘shopping’, ‘parks’, and others, and give weighted scores for distances to get to the respective amenities.

Pedersen and VanMater (2013) generated a city based on branching of both a salt-water canal system and the road system. He used a formula to define branches and another power law function formula to determine footprints and heights of building envelopes. The genetic algorithms changed the way of branching and evaluated the fitness level with a ratio comparing length of waterways generated, number of buildings generated and connectivity of both the road and waterway system.

This paper focuses on developing a design methodology that explores urban configurations at a highly conceptual level. Most of the existing research focuses on specific scenarios, and relatively complex evolutionary algorithms have been developed specifically for those scenarios. In this research, the focus is on trying to develop the simplest possible evolutionary algorithms that can still give meaningful insight into the issue at hand. In this case, the issue is the conflict between travelling time and accessibility to open space for residents in the town. The performance indicators are purely geometric (based network analysis and proximity calculations) and do not take into account system dynamics of the transport systems within the city. However, it is argued that the results of the exploration provide intriguing starting points for further analysis using more detailed simulation models.

3. Evolutionary Exploration Method

The exploration method uses evolutionary algorithms to evolve a population of design variants with respect to certain quantifiable performance criteria. This method requires the designer to define a development procedure that generates design variants and a set of evaluation procedures to evaluate design variants (Janssen et al, 2011b). Lastly, a feedback procedure is used to ensure that design variants are continuously reproduced and evolved through the inheritance of desirable traits. For this research, the Dexen distributed evolutionary system was used (Janssen et al, 2011a), thereby allowing the evolutionary process to be accelerated.

The development procedure must generate design variants based on only a small number of genes, and the evaluation procedures must calculate global performance metrics that represent the performance of the design variant as a single numeric value that can be either maximized or minimized (Janssen et al, 2011a). Furthermore, thousands of design will need to be developed and evaluated, and as a result it is essential that these procedures are fast to execute. For these reasons, the development and evaluation procedures use highly abstracted models. The development procedure generates design variants that consist of highly simplified transport networks with urban density represented as extruded blocks on a square grid. The evaluation procedures calculate simplified performance indicators for travelling time for residents, the amount of open space available to each resident, average block height and the cost of building the transport network.

3.1. DEVELOPMENT PROCEDURE

Based on the assumption that each person needs 50 m^2 of space (including residential, commercial, and other facilities), a total gross floor area of 5 km^2 is required. A blank 1 km^2 site is assumed, with one Mass Rapid Transport (MRT) station located at the centre, connecting it to other towns and the Central Business District. Within the site itself, two types of public transport systems are assumed to be available: a People Mover System (PMS) for travel over intermediate distances and a bus system for more localised travel.

The site boundary and the position of the main MRT station are predefined and the centre of the town is assumed to be located at the MRT station. The development procedure generates design variants by first creating the transport network connecting the town centre to surrounding areas and then creating urban density around the transport nodes, with decreasing density as the distance from the transport node increases.

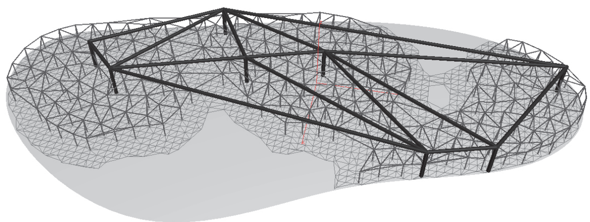

Figure 1. Abstracted model of the transportation networks, consisting of a pedestrian network at the bottom, a bus network in the middle, and a PMS network at the top.

The transport network is represented as a connected set of lines at different heights (see Figure 1). The top level represents the PMS network, the middle level represents the bus network, and the bottom level represents the pedestrian network. The PMS and bus networks are defined by a set of points connected with straight lines. In the case of the PMS, the points represent stations, while in the case of the bus, the points represent bus stops. The pedestrian network is represented as an orthogonal grid of streets.

The development procedure starts by defining the position of the PMS stations. The total number of stations is set to 8 stations based on the area of the site and the number of residents. The position of each PMS station is defined by a pair of genes that define a position (u and v coordinates) on the site. In order to generate the connections between the PMS stations, the station points are triangulated to form "well-shaped" triangles (roughly similar sizes without acute angles).

The bus network is created by generating a bus stop node at each PMS station, and then clustering a set of additional bus stop nodes around each station. The average distance between the bus stop nodes is defined by a gene, thereby allowing the evolutionary system to generate bus networks of varying density. The bus stop nodes are triangulated to form the network of bus connections, and additional bus stops are then inserted along each connecting line. In this way, the bus network connects the PMS stations to the surrounding areas.

Bus stops are clustered around PMS stations in circular zones. The radius of each zone is defined by Equation 1. The radii of these zones start small and get progressively bigger as they get further from the town, with the exception of the town centre which has a fixed zone radius of 500 meters.

$$r = \left(m / \left(\max_i m_i\right)\right)^{0.5} \times 500 \tag{1}$$

where r is the radius of the bus stop zone, m is the distance from the selected PMS station to the MRT station , and $\max_i m_i$ is the maximum of the set of all m distances.

The pedestrian network is created by generating a regular grid on the ground for all areas within a 100 meter distance from any bus stop. The relatively small distance of 100 meters was set in order to ensure that compact towns would be generated where all residents could easily access public transport.

Finally, urban density is generated in all areas directly accessible from the pedestrian network. Urban density is visually represented by extruding a square block vertically, with the height of the extrusion set to vary in relation to the proximity to the closest PMS station. The heights are also represented by vertical lines (lift lines) connected to the transportation network model (see Figure 2). One key constraint is the total floor area, which is fixed at 5 km^2. The extrusion height is therefore determined in a two-step process. In the first step, the height factor is calculated using Equation 2 (see Figure 2). The equation causes the height of extrusion to decrease exponentially as the distance to the closest PMS station increases. The power value, denoted by g, is defined by a gene in the range 0.1 to 0.9. This allows the evolutionary system to vary the rate at which the density falls off.

$$hf = \left(p / \left(\max_i p_i\right)\right)^g \tag{2}$$

where hf is the height factor, p is the distance from the selected block to the closest PMS station, and $\max_i p_i$ is the maximum of the set of all p distances.

The extrusion height is then calculated using Equation 3. In order to achieve 5 km^2 of floor area, and assuming a typical floor plate of $400m^2$, a total block height of 37,500 m is required. The extrusion height for a particular block is calculated by multiplying this total block height by the fraction of the height factor relative to the sum of all height factors.

$$eh = \frac{hf}{\sum_{i=0}^{n} hf_i} \times 37500 \tag{3}$$

where *eh* is the extrusion height, *hf* is the height factor of the selected block, and $\sum hf_i$ is the sum of all the height factors.

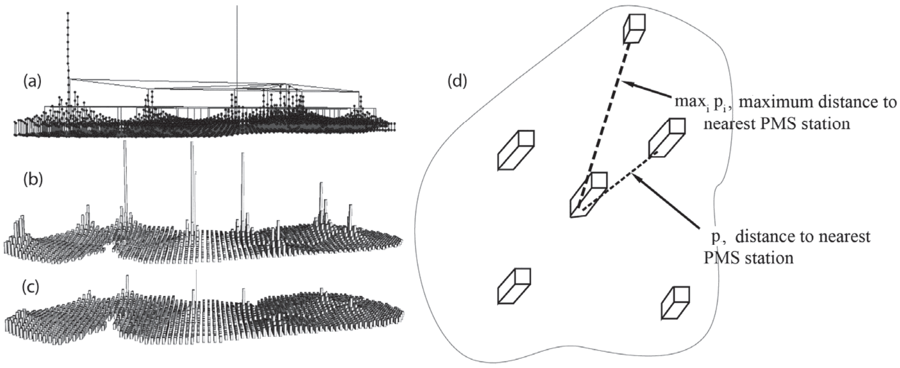

Figure 2. Lift lines in transportation network model (a), examples of a g value 0.8 (b) and a g value of 0.4(c), distances used to define extrusion height (d).

3.2. EVALUATION PROCEDURES

Four indicators are used to evaluate and optimise the urban configuration. They are travelling time indicator, open space indicator, transport infrastructure cost indicator and average building height indicator.

3.2.1 Travelling Time Indicator

The travelling time indicator refers to an indication of times needed to get around the town. Two types of trips are considered: traveling to the town centre and travelling across town (to visit friends). The indicator will take the sum of both travelling times and is set to be minimized so that the town is optimized for travelling.

In order to calculate the approximate travelling time between two points, the shortest path (in terms of travelling time) through the transport network is calculated. This calculation takes into account the travelling speeds for the different transport modes and waiting times when switching between transport modes. For example in Figure 3, the shortest path from A to B was to get down from residential block at point A, walk to a nearest PMS station, wait 3 minutes for an PMS to arrive and ride the PMS to reach the station nearest to B and continue the journey on foot to B. The horizontal and vertical lines of the PMS network are encoded with a train speed of 40 km/h and a waiting time of 3 minutes respectively; horizontal and vertical lines of the bus network encoded with bus speed of 30 km/h and a waiting time of 4 minutes respectively; and the horizontal lines of the walking grid are encoded with a walking speed of 30 m/min.

In order to calculate an overall travelling time for a particular town, 100 trips to the town centre and 100 trips to visit friends were calculated. For the trips to the town centre, starting points were chosen randomly. For the trips to across town, both starting points and destination points were chosen randomly. The travelling time indicator is calculated as the sum of both types of trips.

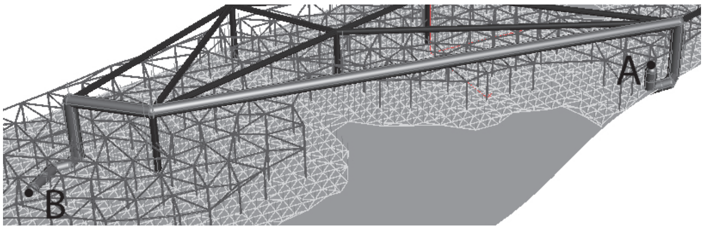

Figure 3. Calculation of shortest path between two points, A and B.

3.2.2. Open Space Indicator

The open space indicator calculates the amount of open space directly adjacent to the built up areas, as this is the area that is assumed to be used by residents in the town. The adjacency threshold is set to 100 meters. Open space is set to be maximised.

3. 2. 3. Infrastructure Cost Indicator

The transport infrastructure cost indicator calculates the sum of the weighted lengths of both the bus network and the PMS network. The PMS network is assumed to be twice as costly as the bus network for a given length. The cost is set to be minimised.

3. 2.4. Block Height Indicator

The block height indicator calculates the average of the block heights, measured in terms of the number of floors. This indicator gives an approximation of average density and is inversely related to site coverage. Block height is set to be minimized.

4. Results

The evolutionary exploration process generated a total of 20,000 urban configurations, resulting in a final population of 100 optimised configurations. Figure 4 show selected designs from the final population.

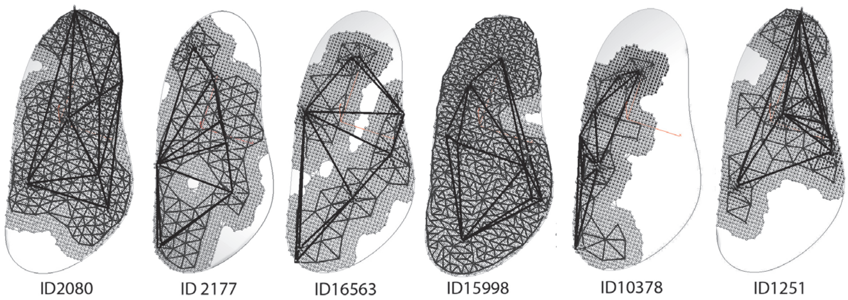

Figure 4. Visualisations of a set of evolved designs

4. 1. GENERAL TRENDS

In order to better understand the relationships between the performance indicators, a number of graphs were plotted for pairs of indicators. From the graphs, certain general trends can be identified.

The Travelling Time versus Open Space graph in Figure 5 (top) shows a general trend of travelling time increasing together with open space. For example, comparing ID2080 and ID16563, higher block heights resulted in higher open space but with longer travelling times. The Traveling Time versus Infrastructure Cost graph in Figure 5 (bottom) shows a general trend of travelling times increasing as the cost of transportation network decreases. For example, comparing ID1251 and ID15998, the very dense and extensive bus network resulted in higher infrastructure costs and lower travelling times.

4. 2. URBAN TYPOLOGIES

Analysis of the final population of evolved design resulted in the identification of three main urban typologies, referred to as 'compact town', 'segregated town' or 'stretched town', as shown in Figure 6.

- A compact town has a single compact built-up area surrounded by open space. It tends to favour travelling time over open space.
- A segregated town has open spaces separating clusters of built-up areas. It tends to favour open space over travelling time.
- A stretched town has a built-up area that meanders through the site. It tends to find a balance between travelling time and open space.

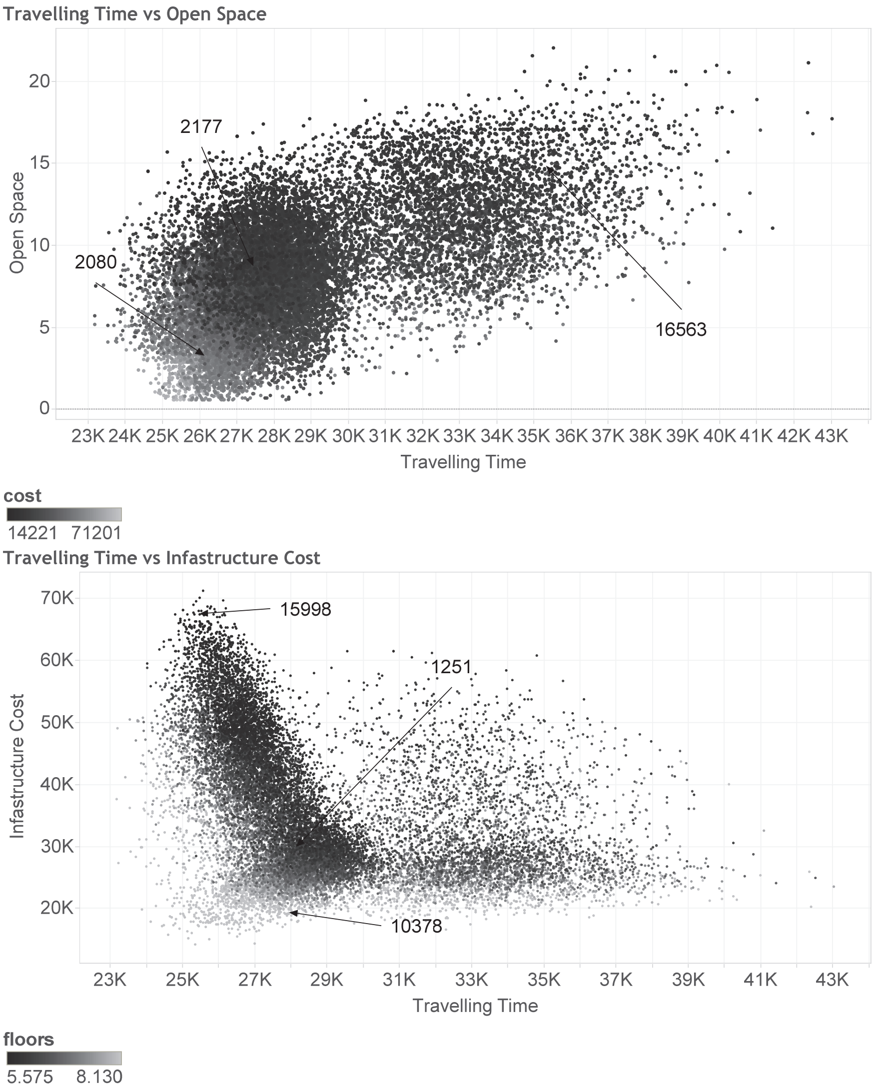

Figure 5. Graphs of Traveling Time versus Infrastructure Cost (top) and Traveling Time versus Open Space (bottom)

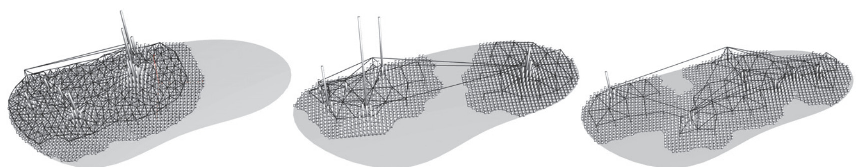

Figure 6. Compact Town (left), Segregated Town (middle), Stretched Town (right)

5. Conclusions

This paper proposed an evolutionary approach to exploring urban configurations. The exploration process resulted in a population of urban configurations, where each configuration represents alternative trade-off between a set conflicting performance criteria. Within this population, clusters of solutions were identified with common typologies. Three differing typologies were identified as possible starting points for more detailed design development taking into account a broader set of social, environmental, and economic issue.

In order to be able to effectively test the potential of the proposed approach, a highly simplified urban planning scenario was used. Future research will start to add further complexity to this scenario in three main ways. First, with regards to the urban configurations being evolved within the site, the evolutionary procedures will be enhanced to be able to manipulate a richer set of programs, focusing in particular on facilities that play a significant role in people's daily lives, such as schools and malls. Second, with regards to the conditions within the site, the evolutionary procedures will be enhanced to take into account site features that impose constraints on the proposed urban configurations, starting with topography and water-bodies. Third, with regards to existing conditions adjacent to the site, the evolutionary procedures will be enhanced to take into account surrounding urban areas such as neighbouring towns and villages.

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