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PLOT PACKING

A procedure for generating well-formed street networks

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Abstract. Generative design tools can accelerate the optioneering process by allowing designers to quickly generate large numbers of design variants, thereby enabling a wider and more thorough exploration to be conducted. This paper focuses on procedures for generating inner city street networks and city block massing studies for sites within existing urban areas. A novel procedure is proposed that is capable of subdividing complex non-orthogonal sites into similarly sized well-formed plots and subsequently further subdividing these plots into sizes appropriate for selected city block typologies. The application of the procedure is demonstrated on a site in Singapore.

Keywords. Urban optioneering; street networks; parametric urbanism; quadrilateral mesh generation.

1. Introduction

Urban optioneering involves the systematic exploration of options for urban design proposals (Holzer and Downing 2010). Generative design tools can accelerate the optioneering process by allowing designers to quickly generate large numbers of design variants, thereby enabling a wider and more thorough exploration to be conducted. Furthermore, the use of such generative tools will often lead to better quality designs that could not have been developed using conventional design methods.

At the urban level, optioneering processes typically require procedures for generating city street networks and city block massings. We refer to these types of procedures as ‘plot packing’ procedures. This research focuses on inner city type of hierarchical street network, consisting of plots surrounded on all sides by streets, with no dead ends and with streets that tend to be fairly straight (rather than curvilinear, as is the case in some suburban street networks).

This research considers only the geometric issues, with the aim being to develop procedures for generating well-formed street networks. However, urban planning and design must clearly take into consideration a much wider set of issues, including social, economic, and environmental issues. It is assumed that if used in practice, the proposed procedures would only constitute one tool within a broader set of tools of generating and evaluating urban design proposals.

Previous researchers have developed a number of procedures for generating street networks using a variety of computational techniques, including particle systems, L-Systems, and grammars. Parish and Muller (2001) developed the CityEngine software for generating city models using a number of different L-System models. The software generates highways, streets, and buildings. Highways connect predefined areas of high population, while the land between the highways is divided into smaller areas surrounded by gridded streets. Beirao and Duarte (2005) have developed an approach using urban grammars in which a wide variety of street networks and plot layouts can be generated by recursively applying user-defined shape grammar rules. These rules can either be developed from scratch or can be based on an analysis of the existing urban fabric. Braach and Fritz developed the Kaisersrot parcelling software that was used on a series of projects for generating layouts for low-rise residential developments (Kaisersrot 2000, Lehnerer 2009, Hovestadt 2010). The generative procedure combined a particle system with Voronoi partitioning in order to generate roads and plots.

Subdividing complex non-orthogonal sites into similarly sized orthogonal plots is a complex task. The procedures developed by previous researchers have been found to give insufficient control over the plot shapes and sizes that are generated. This research has therefore set out to develop an alternative procedure for street network generation.

Section two gives a detailed description of the proposed procedure. Section three gives an example of how this procedure can be applied to a site in Singapore. Finally section four discusses the limitations of the current procedure and identifies future areas of research.

2. Proposed Procedure

A plot packing procedure is required that is capable of generating street networks and plots with the following key features:

- generate street networks within sites with irregular shapes, possibly including sites with concave shapes,
- generate street networks that connect to existing surrounding streets at predefined points along the perimeter of the sites,
- generate street networks that include different categories of streets, such as primary and secondary streets,
- generate street networks where streets tend to be fairly straight and where intersections tend to have either three or four streets,
- generate street networks that result in evenly sized plots that tend to be close to orthogonal in shape.

The proposed procedure starts with a planar polygon representing the site and then generates street and building massings as follows:

- Stage 1: A regular triangulated mesh with evenly shaped triangles is generated over the entire site area.
- Stage 2: A quadrilateral mesh is generated from the triangulated mesh through a process of merging triangles.
- Stage 3: Street networks of differing categories are generated by subdividing quadrilaterals to form smaller quadrilaterals.
- Stage 4: Building massings based on selected typologies are generated within the plots defined by the street networks.

Each of the stages is described in more detail below.

2.1. GENERATION OF TRIANGULATED MESH

The quality of the street networks generated in the later stages depends to a large degree on the regularity of the underlying triangulation. Regular meshes consist of triangles that are close to equilateral and that have similar edge lengths.

Many CAD systems incorporate tools and algorithms for working with triangulated meshes and in some cases these may include tools for generating regular triangulations. For this research, a modelling system called Sidefx Houdini is used, which includes such a tool. The density of the triangulation is controlled by the target length of triangle edges, which is specified by the user as a parameter.

An alternative approach would be to create a customized procedure for generating such meshes. One option for such a procedure would be to use a particle system (Shimada 1993). The site boundary is defined as barrier to the particles, and the desired radius of the particles is defined. The particles are then randomly inserted and then allowed to distribute themselves evenly through a process of mutual repulsion. Once a stable arrangement is achieved, the centre points of the particles can then be triangulated.

Whatever procedure is used for generating the triangulated mesh, one important constraint is that it should be possible to define certain points along the perimeter of the site polygon where mesh lines will be generated. The reason for this is that, in Stage 3, these lines will become streets. Being able to specify points where mesh lines will be generated will ensure that the streets that get generated within the site also connect to the surrounding street network.

2.2. GENERATION OF QUADRILATERAL MESH

As with triangulated mesh, quadrilateral mesh are required that have a high degree of regularity. Regular quadrilateral meshes consist of quadrilaterals with interior angles that are close to right angles.

The procedure is proposed that converts triangulated meshes into quadrilateral meshes using three basic algorithms.

- **Merge triangle pairs:** pairs of adjacent triangles are merged to form quadrilaterals. (See Figure 1 (a)).
- **Merge isolated triangles:** isolated triangles are merged with neighbouring quadrilaterals and then split into two quadrilaterals. (See Figure 1 (b)).
- **Fix irregular quads:** irregular quadrilaterals are merged with a neighbouring quadrilateral and then split into three quadrilaterals. (See Figure 1 (c)).

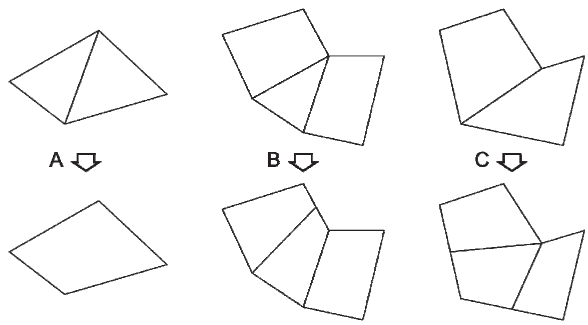

Figure 1: Three algorithms used to generate regular quadrilateral meshes: (a) merge triangle pairs (b) merge isolated triangles, and (c) fix irregular quads.

The main *merge triangle pairs* algorithm selects adjacent pairs of triangles and merges them. However, depending on order in which triangles are merged, certain isolated triangles will remain that cannot be merged. The *merge isolated triangles* algorithm merges each of these isolated triangles with one of the neighbouring quadrilaterals to form a five sided shape, and then splits this shape into two quadrilaterals. For each isolated triangle, there are a maximum of 15 possible ways of merging and splitting. In order to select the one that results in the most regular quadrilaterals, all 15 merge-split operations are performed, and the resulting quadrilaterals are then analysed. For this, a scalar function is defined that measures the regularity of a quadrilateral by calculating the sum of the absolute values of the cosines of the four interior angles (see Itoh at al. (1995) for more details), giving a score between 0 and 4. Of the 15 possible merge-split operations, the one resulting in the quadrilaterals with the highest scores is chosen.

Finally, the processes of merging triangles may result in some quadrilaterals that are very irregular. The *fix irregular quads* algorithm merges each of these irregular quadrilaterals with one of the neighbouring quadrilaterals to form a six sided shape, and then splits this into three quadrilaterals. In this case, in order to ensure that regular quadrilaterals are generated, the six sided shape should form an L-shape, which is then easily split into three quadrilaterals, with one in the corner of the L and two at the ends of the L.

With regards to the regularity of the final quadrilateral mesh, the key to this procedure is the order in which triangle pairs are merged. Some orderings will result in very regular meshes while other orderings will result in very irregular meshes. Finding the best ordering is a non-trivial problem, and a optimization algorithm is therefore used. A hill climbing algorithm is defined as a solver that iteratively explores different orderings by creating new orderings based on the best ordering it has found at that stage. For each ordering, the solver executes all three algorithms described above and if the new ordering results in a higher quality mesh, it will replace the previous best ordering. Figure 2 shows meshes generated at different stages of the solver optimisation process.

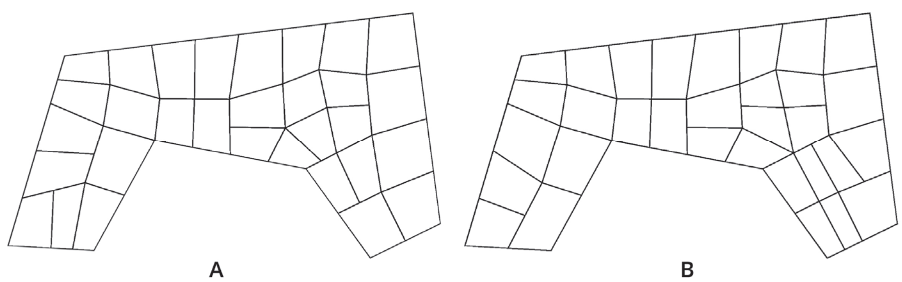

Figure 2: Quadrilateral meshes generated at two stages of the solver optimization process: (a) at iteration 1 and (b) at iteration 100.

In order to be able to compare two orderings, the solver needs a way of measuring the quality of the quadrilateral mesh. The quality of the mesh is calculated as the average of the worst 50% of quadrilaterals. The aim of the solver is therefore to try and find orderings that improve the worst quadrilaterals.

The final remaining issue for the quadrilateral mesh procedure is how to generate the initial ordering. Using a random ordering is likely to result in a very poor initial mesh. An initial ordering algorithm is therefore proposed, based on method by Itoh et al. (1995). With this algorithm, a list is first created of all possible pairs of adjacent triangles. The list is then sorted from best to worst, according to the quality of the quadrilaterals that would result from merging each triangle pair. An ordering is then generated by selecting triangle pairs from the top of the list down. The mesh resulting from the initial ordering is shown in Figure 2(a).

2.3. GENERATION OF STREET NETWORKS

The quadrilateral mesh is then subdivided to form a well-formed street network using a subdivision algorithm. This algorithm splits quadrilaterals according to a minimum edge length, which is specified by the user as a parameter. For this minimum edge length, the maximum number of smaller quadrilaterals is calculated, and the original quadrilateral is then split by dividing the edges equally.

Depending on the type of street network that is required, the quadrilateral can be split either in one direction only, or in two directions at the same time.

- If the quadrilateral is split in two directions at the same time, then the quadrilateral is being cut into a grid. (In Figure 3, see (f) to (g)).
- If the quadrilateral is split in one direction, then the quadrilateral is being cut into strips. An additional parameter is used to define whether the strips are cut in the long direction or the short direction. (In Figure 3, see (f) to (i)).

Once the smaller quadrilaterals have been generated, then it may still be possible to subdivide some of these smaller quadrilaterals again. The subdivision algorithm is therefore applied recursively, with the maximum depth being specified by the user as a parameter.

The streets are generated by insetting the quadrilaterals adjacent to those streets by a distance equal to half the street width. The insetting is performed as soon as one category of streets has been fully generated, thereby allowing each street category to have a different width.

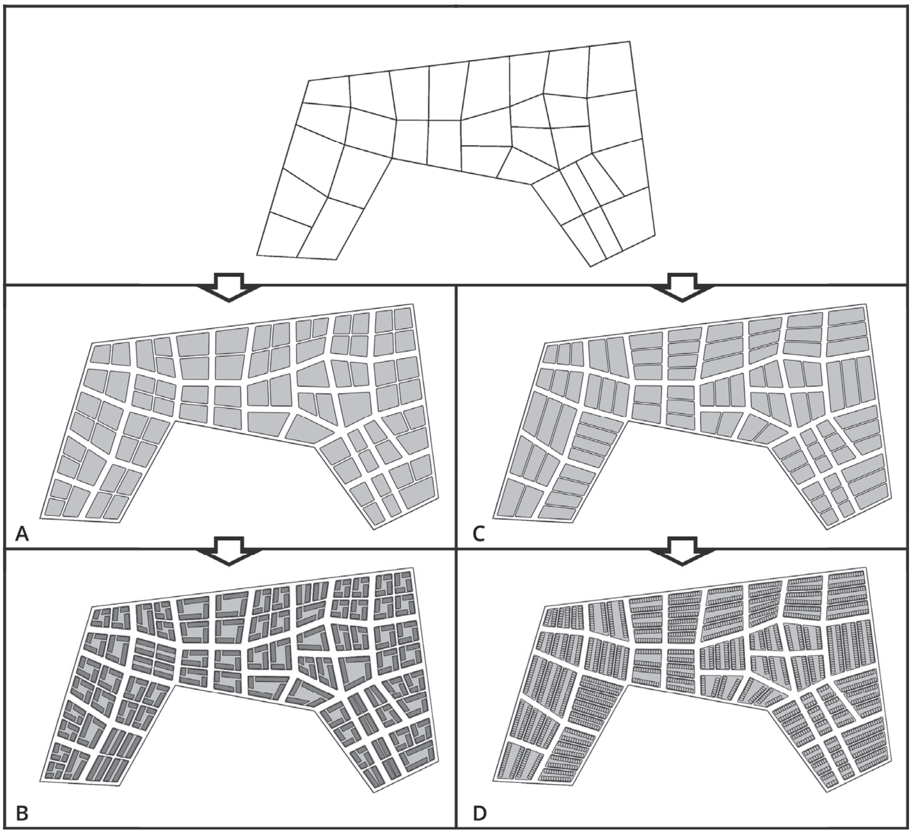

Figure 3: Generation of street networks and building massings: (a) and (b) perimeter block typology, (c) and (d) row house typology.

2.4. APPLICATION OF CITY BLOCK TYPOLOGIES

The generation of the street network results in a set of quadrilateral building plots. Due to the procedure used for generating the network, the city block plot will in general be well-formed without acute angles.

For the next stage, city blocks are generated for each plot based on a selected typology. It is envisaged that a library of parametric models could be developed, so that different options could be explored with a wide range of varying typologies. For each typology, a parametric model would be developed that would adjust itself to the boundary of the plots into which it was inserted and create massing volumes according to certain rules.

Currently, two typologies have been implemented:

- A perimeter block typology consisting of four 12 meter deep linear blocks parallel to the edges of the plot, with an open courtyard space in the centre.

The blocks consist of commercial spaces at the ground floor and residential apartments above. The height of each block is variable, ranging from 4 floors to 8 floors (see Figure 3, (g) to (h)).

- A row house typology consisting of linear rows of units arranged along pedestrianized roads. The height of the units are fixed at 4 floors, with a ground floor flat on levels 1 and 2, and an upper flat on levels 3 and 4 accessible via a shared staircase (see Figure 3, (i) to (j)).

3. Case Study

In order to demonstrate how such generative design tools can be used to support urban optioneering, a site in Singapore has been selected as a case study. Located in the central region of Singapore, the site has an area of 93 Ha and the proposed plan is to build 11,000 public housing flats. The current design has a standard Singapore typology consisting of point block residential towers distributed throughout the site with a park in the centre. The gross plot ratio of the site is calculated to be approximately 1.5.

3.1. APPLICATION OF TYPOLOGIES

For the demonstration, a density exercise was conducted for the Bidadari site. A plot ratio of 1.5 was used as a target density and a series of alternative options were rapidly generated based on the two typologies presented above: one set of options for the perimeter block typology and another set of options for the row house typology. Figure 4 shows two selected options.

Given a more extensive library of typologies, urban designers would quickly be able to explore a wide variety of urban options with real-time feedback on key metrics such as overall density, amount of open space, number of car parking spaces, and so forth.

4. Conclusion

A novel procedure has been proposed that is capable of subdividing complex non-orthogonal sites into inner city street networks with similarly sized orthogonal plots and subsequently further subdividing these plots into sizes appropriate for selected city block typologies. The application of the procedure is explored on a site in Singapore, showing how such procedures might be applied in optioneeering studies.

Figure 4: The perimeter block and row house typologies applied to the Bidadari site.

Future research will expand on this research in three main ways. First, the current approach does not easily accommodate additional constraints on street networks mainly due to the simplicity of the solver. The quadrilateral generation procedure will be updated, replacing the hill-climbing algorithm with a multi-objective evolutionary algorithm that can potentially take into account additional constraints. Second, in the current approach, the site is assumed to be blank (without any existing elements, such as roads, building, and water elements). The street network procedure will be expanded to allow for the inclusion of obstacles in the site where neither roads nor buildings can be added. Third, the application of typologies currently assumes that the same typology will be applied in all areas. The city block procedure will be updated to allow the user to define how typologies could be mixed in order to generate more varied urban environments.

As mentioned in the introduction, when developing the urban form of a neighbourhood, it is assumed that planners and designers would apply such procedures in conjunction with a wide range of other tools and techniques for generating and evaluating designs. Once the proposed procedures have been further developed, their use with more realistic scenarios in conjunction with a broader toolset can be explored.

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