EXPLORATION OF URBAN STREET PATTERNS

Multi-criteria evolutionary optimisation using axial line analysis

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Abstract. In urban design, researchers have developed techniques to automate both the generation and evaluation of urban street patterns. In most cases, these approaches are investigated in isolation from one another. Recently, a number of researchers have attempted to couple these approaches, in order to enable larger numbers of street patterns to be generated and evaluated in an iterative loop. However, to date, the possibility of fully automating the generative-evaluative loop using optimisation algorithms has not been explored. This research proposes an explorative design method in which urban street patterns can be optimised for multiple conflicting performance criteria. The optimisation process uses evolutionary algorithms to evolve populations of design variants by iteratively applying three key procedures: development, evaluation, and feedback. For development, a generative technique is proposed for constructing street patterns. For evaluation, various performance measures are used, including in particular Space Syntax based Axial Line analysis. For feedback, a Pareto-ranking algorithm is used that ranks street patterns according to multiple criteria. The proposed method is demonstrated using an abstract scenario in which orthogonal street patterns are evolved for a small urban area.

Keywords. Axial line analysis; generative modelling; evolutionary algorithms; decision chain encoding; urban street patterns.

1. Introduction

The idea of automating certain parts of the urban design process has been around since 1960s. Since then, researchers have developed a wide variety of techniques to automate both the generation and evaluation of urban design. This research will focus in particular on the generation and evaluation of street patterns.

For generating street patterns, researchers have investigated a number of generative techniques. Duarte et al. (2006) described the generative modelling of the

Medina of Marrakech by combining a top-down and bottom-up hybrid models. Braach and Fritz (2010) used Voronoi partitioning in the generative modelling of street patterns. Both Parish and Muller (2009) and Chen et al. (2008) generated urban street patterns using Lidenmayer systems (L-systems).

For evaluating street patterns, researchers in the field of Space Syntax have since the 1970s been developing and refining various tools and theories (Hillier and Hanson, 1984; Hillier, 1996; Hanson 1998). Space Syntax methods translate overlapping convex spaces into a series of graph structures that can be analysed and interpreted in terms of their two-dimensional spatial characteristics. One of the key methods is the *Axial Line* method, which creates such a graph by generating a set of overlapping sight lines, referred to as *Axial Lines*.

For Axial Line methods, the main concepts are that of *depth* and *integration*. Depth described the minimum number of Axial Lines that need to be traversed in order to get from one space to another space. Integration describes the minimum depth between one space and all other spaces. Integration can also be calculated for a certain radius *n*, in which case it measures the total number of spaces that can be reached from a particular space by traversing *n* Axial Lines. Integration at a low radius (for example n = 3) is referred to a *local integration*, while integration without specifying any radius is referred to as a *global integration*.

Depth and integration are measures associated with particular spaces within a spatial configuration. However, these measures can also be used as a basis for calculating some more general measures that describe characteristic of the overall spatial configuration. Two such measures are the *mean depth* and the R^2 *correlation*. The mean depth measures the mean of all the depths from every space to every other space in the spatial configuration. A low mean depth may be desirable, as it is seen to represent better integrated spatial configurations. The R^2 correlation is slightly more complex. To calculate R^2, both local and global integration values are calculated for every space in the spatial configuration, and a scatter plot is generated of local versus global integration. The R^2 correlation is then calculated as the statistical correlation between these two sets of values, also referred to as the *coefficient of determination*. A high R^2 correlation may be desirable, as it is seen to represent the intelligibility of the spatial configuration (Hillier, 2002).

Research using Axial Line methods focuses mostly on the analysis of existing street patterns rather than the synthesis of new street patterns. A number of researchers have been exploring how these techniques can be used as a way of evaluating alternative urban design proposals. Hillier et al. (2008) used Axial Line analysis to evaluate design proposals in the Jeddah Urban Regeneration Master plan. Existing urban fabric and the old local plan were examined in order to observe the connectedness of neighbouring towns to the historic core. The proposed design option was then simulated to predict its effectiveness. Stonor (2009)

showed similar evaluation of the design proposal for Trafalgar Square, London. Both cases used Axial Line analysis in an "analyse, observe, predict" framework.

Recently, a number of researchers have combined generative urban modelling and Axial Line analysis in an iterative manner, where each iteration is applied manually. For example, Al-Sayed (2012) used Axial Line analysis to evaluate different iterations for hypothetical urban street patterns. Generative modelling techniques were used to create a variety of street patterns, which were subsequently evaluated for their R^2 correlation. Certain street patterns were then selected and further analysed. In another experiment, Canuto (2012) created different iterations of an abstracted urban grid followed by evaluation using Axial Line measures, as well as a set of other measures known as *urbanity ratios*. Both experiments showed the possibility of iteratively combining the generation and evaluation of urban street patterns to optimise a number of design variants.

Despite significant research in the areas of urban street pattern generation and evaluation, no research has explored the automated optimisation of street patterns using optimisation algorithms. This paper proposes such a method for the automated evolution of street patterns. The proposed method is demonstrated using an abstract scenario in which orthogonal street patterns are evolved for a small urban area.

2. Demonstration

The proposed method combines three techniques: the generative modelling of street patterns (generation), Axial Line analysis of street patterns (evaluation), and optimisation of street patterns using Evolutionary Algorithms.

Evolutionary design (Frazer, 1995; Bentley, 1999; Caldas, 2001; Bentley, and Corne, 2002; Janssen, 2004) is an approach that evolves populations of design variants through the iterative application of a set of computational procedures. The developmental procedure generates design variants, one or more evaluation procedures assess the performance of design variants, and the feedback procedure drives the evolutionary process by applying selective pressure to the population.

The use of Evolutionary Algorithms allow large numbers of alternative design variants to be considered in a fully automated way, thereby allowing optimised street patterns to be generated. The Evolutionary Algorithms here act as a way of "closing the loop" between generative modelling of street patterns and Axial Line analysis of street patterns.

The evolutionary process is executed using Dexen, a distributed execution environment for population based algorithms (Janssen et al., 2011). This system is coupled to a procedural modelling environment called SideFX Houdini, which is used for creating both the developmental and evaluation procedures (Janssen and Chen, 2011). The feedback procedure is generated automatically by Dexen, and

uses a Pareto-ranking algorithm that ranks street patterns according to multiple criteria. The results of the evolutionary process are plotted as a scatter plot using a data analytics package called Tableau.

2.1. DEVELOPMENTAL PROCEDURE

For the developmental procedure, a generative technique called *decision chain encoding* is used to generate street patterns (Janssen and Kaushik, 2013). The decision chain encoding technique structures the street pattern generation process as a sequential chain of decision points, where each decision consists of a 'design move' that inserts an urban block into the urban grid. Each time a block needs to be inserted, a gene will be used to select a move from a list of possible valid moves.

The starting condition for the developmental procedure consists of a library of urban blocks together with an empty urban area with a boundary condition at the periphery. The task is then to fill the empty urban area with some combination of blocks from the urban block library. The way that the blocks are inserted and orientated results in a variety of urban streets and squares with varying spatial qualities. Figure 1 shows the starting condition on the left and six steps in the decision chain process on the right.

The decision chain process continues to add blocks until either no more blocks can be inserted or until a certain maximum is reached. In this case, the maximum
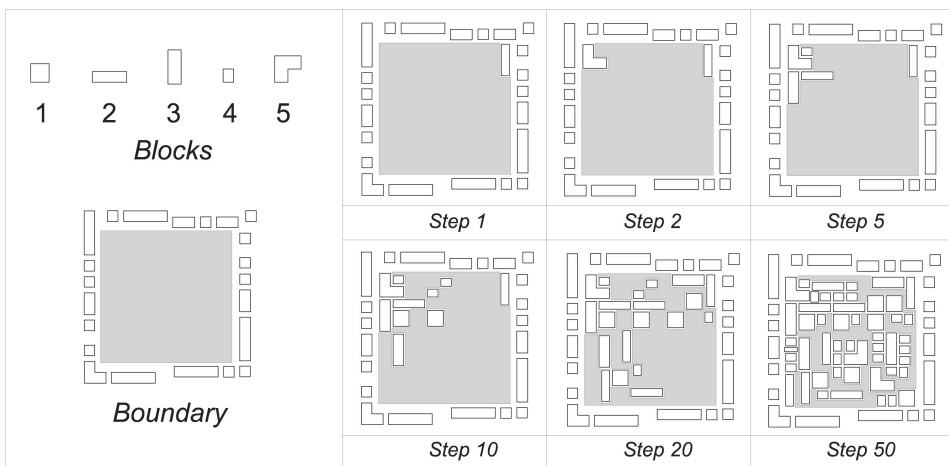

Figure 1. Sequence of generative street modelling.

was set to be 100 blocks (which was in fact never reached). Since 100 blocks require 100 decision points, the genotype is also set to be 100 genes long. Genes are real values in the range {0, 1}, which are used to select valid moves by mapping to an integer range {1, n}, where n is the number of valid moves for that particular decision point.

2.2. EVALUATION PROCEDURES

Three separate evaluation procedures are defined which are used to evaluate each street pattern. The three procedures are used to calculate three performance criteria: the R^2 *correlation*, the *average line length*, and the *total footprint*. The R^2 correlation has already been described above and in this case measures the correlation between local integration with a radius of 3 and global integration. The average line length measures the average length of all Axial Lines. Lastly, the total building footprint measures the total footprint of all urban blocks.

The R^2 correlation is seen as measuring intelligibility, and therefore the optimisation system is set to maximise this performance criteria. One way of achieving this is by generating a regular urban grid with long straight streets. For such a grid, the average line length will therefore be very high. However, research by Hillier (2002) has suggested that historical urban street patterns typically have a few long Axial Lines combined with many short Axial Lines. For the optimisation algorithm, we therefore set the average line length to be minimised. The first two performance criteria are therefore defined to be in conflict with one another, as street patterns cannot have both a high R^2 correlation and a low average line length. Such a conflict is seen as being desirable, as it is likely to result in a range of performance trade-offs. Lastly, in order to encourage the optimisation system to generate high density street patterns, the third performance criteria is added for the maximisation of building footprint.

This research is not suggesting that the selected performance criteria are sufficient as a basis for evaluating the quality of a particular street pattern. Performance criteria will vary on a case-by-case basis and may include a wide range of factors. Rather than being used as a tool for global optimisation, this research imagines such tools to be used in a more exploratory mode. The solutions that are evolved should therefore not be seen as being the best answers, but instead as a provocation for deeper analysis and exploration.

In order to calculate the R^2 correlation and the average line length, Axial Lines need to be generated and analysed. A Space Syntax software tool exists that can be used for this, called Depthmap. However, the tool cannot be easily automated by another program and as a result it was not used in this case. Instead, a custom plugin was created for Houdini. Within Houdini, two separate algorithms were
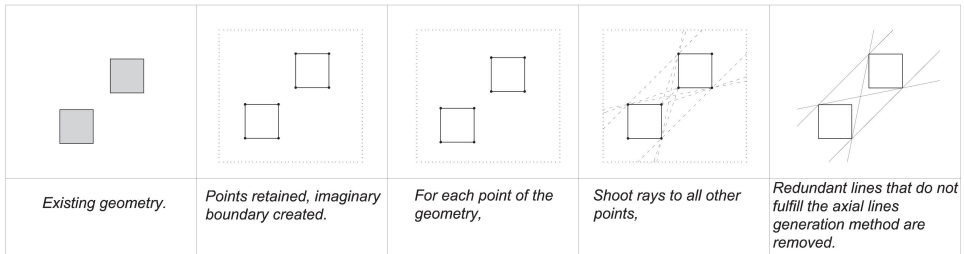
Existing geometry.	*Points retained, imaginary boundary created.*	*For each point of the geometry,*	*Shoot rays to all other points,*	*Redundant lines that do not fulfill the axial lines generation method are removed.*

Figure 2. Axial Line generation in Houdini.

implemented: one for generating the Axial Lines, and another for analysing the Axial Lines. The Axial Line generation algorithm is implemented using built-in ray functions within Houdini following the method described in the Space Syntax literature (Turner et al., 2004; Ostwald, 2011). The Axial Line analysis algorithm first translates the Axial Lines into a graph representation and then calculates integration values. The graph calculations are performed using a general-purpose graph library called NetworkX.

In order to validate the results, a number of tests were carried out, comparing the generation and analysis of Axial Lines in Houdini to the results obtained from Depthmap. Although the Houdini technique was found to generate slightly fewer Axial Lines than Depthmap, there was only a 1.4% difference in *mean depth* and 0.2–5% difference in *integration values*.

Houdini was therefore used to define all three evaluation procedures: R^2 correlation, average line length, and total footprint. The first two required Axial Line techniques while the last one consists of a simple area calculation.

3. Experiment Outcome

The evolutionary system was run with a population of 100 street patterns, for a total of 10,000 births. Street patterns with very low total footprints were first filtered out, resulting in 5500 remaining street patterns. A scatter-plot was created where each point represents a different street pattern. For the scatter plot, the R^2 *correlation* was plotted against *average line length*. The scatter plot is shown at the centre of Figure 3. Dark circles represent street patterns with larger total footprints, while light circles represent street patterns with smaller total footprints.

In the scatter plot, the most desirable area is the top-left corner, where the average line length is minimised and the R^2 correlation is maximised. The closer a point is to this area, the higher its rank. Conversely, the further away they are from this area, the lower their rank.
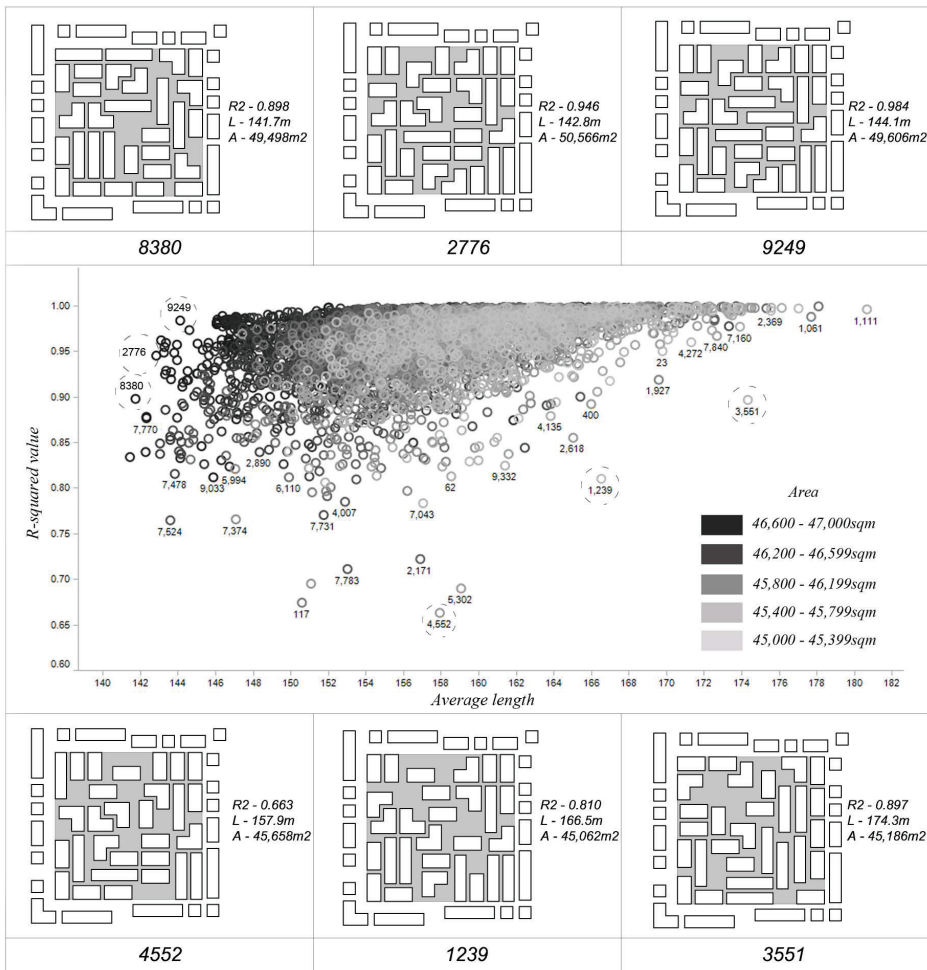
Figure 3. Scatter plot of 5500 individuals.

Various street patterns were selected to be examined in more detail. Figure 3, the three street patterns at the top have a high rank while the three street patterns at the bottom have a low rank. At first sight, it is hard to tell why one set would be more highly ranked than another set. However, certain key characteristics can be identified.

In general, the high rank street patterns have grid-like configurations where the urban blocks are evenly distributed and densely packed, thereby resulting in a high total footprint. They typically include a number of long, straight streets. These make the journey from one end of the street pattern to the other end easier as more
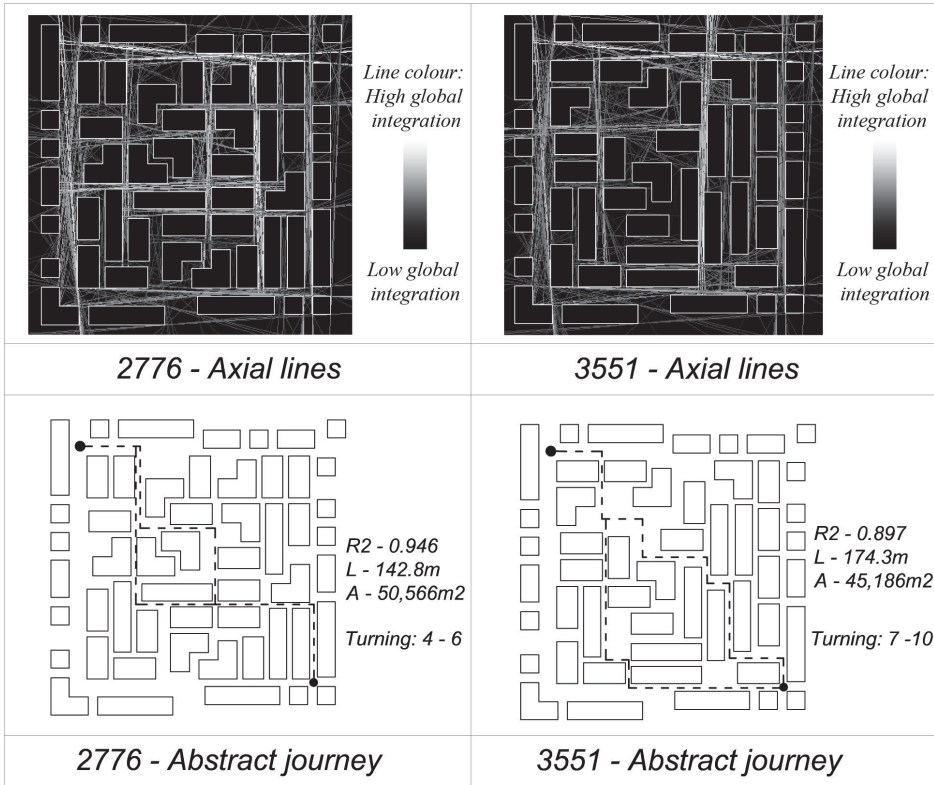
Figure 4. (a) Individual 2776 (b) Individual 3551.

direct routes can be used. The locations of open spaces are more well defined and easily accessible (Figure 4a).

In contrast, the low rank street patterns exhibit a more random configuration. The urban blocks are tightly packed in some areas and loosely distributed in other areas with some large open spaces in-between, thereby resulting in a low total footprint. This makes the journey from one end to another more complex (Figure 4b).

Overall, the highly ranked street patterns seem to have a more legible spatial pattern as compared to the lower ranked street patterns. This represents one phase in the evolutionary exploration process. Subsequent phases would tweak the generative technique in order to generate street patterns that differ more significantly with regards to R^2 correlation and average line length. In particular, increasing the block library to include a wider variety of urban blocks may result in more tightly interlocking patterns.

4. Conclusions

This paper has demonstrated how evolutionary algorithms can be used to link generative modelling techniques to Axial Line evaluation techniques. This suggests an alternative explorative design method for the early phases of urban design, when overall urban patterns and textures need to be developed. Future research will further develop this design method taking into account a wider range of performance criteria, including in particular environmental criteria such as solar radiation and daylight.

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