THE URBAN GENOME

A framework for multi-objective environmental optimization

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Abstract: The influence of urban morphology on the energy consumption of a fabric has been recently established by research into the energy use of existing cities. This paper suggests a framework for generating environmentally adapted urban tissue by using genetic algorithms as form-finding processes. A series of multi-objective optimization algorithms are described. The geometric abstractions used as a basis for these algorithms are illustrated in detail, and the results and implications of these types of simulations are discussed. The methodology developed within this paper was tested on one km² site in three cities of varying climates, and further expanded into a detailed case study within one city.

Keywords. Urban simulation; Environmental design; Optimization; Genetic Algorithms; Urban Morphology.

1. Introduction

There is a growing interest in utilizing performance-driven computational design methodologies as analytical evaluation tools within an iterative design process. Typical architectural practice tends to conduct the environmental simulation of a building’s behaviour after a specific design option has already been decided upon and further elaborated. A more contemporary approach suggests integrating generative algorithms with evaluative criteria into the form-finding process itself (Oxman, 2008). In this paper a complete generation – evaluation loop is suggested, encoded into the Grasshopper / Python computational environment in a way that allows the designer control over the morphological genome of the fabric.
At every simulated scale, the existing context surrounding the site is analysed and quantified into an abstract parametric representation. This genome is used both as a starting point for the algorithmic evolution as well as a basis for comparison with the simulation’s results. Environmental aspects such as insolation, energy use and wind flow at the pedestrian level are scripted into custom Grasshopper components and used as evaluation criteria for the genetic simulation.

The design methodology developed in this paper was tested on sites located in three different cities with three distinct climate zones: Seville, Stockholm and Brooklyn. The overarching goal was that the resulting morphologies both show architectural resemblances to their surroundings as well as be better adapted to the local climate. Further rounds of simulations were performed on the Brooklyn fabric, decreasing in scale to the block and individual building levels.

2. The urban climatic challenge

The impact of urban morphology on the design and development of cities can be found in a number of historical examples such as the old, walled city of Shibam in Yemen. In Shibam the street layout and the orientation of the buildings provides self-shading in order to cool the temperature of the streets as well as the indoor spaces (Helfritz, 1937). In many other cases, vernacular architectures have been adapted to their environments by processes of trial and error evolving over generations.

Recent studies into the energy use of modern urban fabrics have shown that contemporary architecture is not always well-adapted to its local climate. In some cases, entire neighbourhoods are shown to use twice as much energy as adjacent areas built in a similar periods, simply because their morphology is not adapted to local climatic conditions (Salat, 2009). These examples further highlight the possible effects design can have on an urban microclimate, and show the possibility of improving energy consumption by adapting the orientation of streets, as well as block and building massing to a site’s environmental conditions.

Yet when it comes to measuring and quantifying physical data, defining the building typology and linking it to energetic performance is not always a straightforward task. It often becomes necessary to abstract the urban morphology due to the complexity of the actual geometry. The difficulties in evaluating the urban configuration have been noted previously. Adolphe suggests a set of morphological parameters as such rugosity, porosity, sinuosity, etc. as a way to represent the heterogeneous urban context in order to estimate microclimatic conditions such as wind flow and solar access as well
as energy consumption (Adolphe, 2009). Yet these methods are often too ab-
stract and do not respond to small variations in the built environment. In the
following experiments, some of Adolphe’s methods are developed and
adapted for use in the Galapagos environment.

3. Case study I: Three cities

As a study, a Genetic form-finding simulation was performed on three dif-
ferent urban patches, between 0.5 and 1.5 square kilometres in size, with
three very different climates: Seville, Spain (hot climate), Stockholm, Swe-
den (cold climate) and Brooklyn, New York (alternating hot summers and
cold winters). The algorithm was allowed to create variations of the street
network layout as well as on typical sections of each street, while keeping
the overall built volume density to a fixed amount – the same as was meas-
ured on the original fabric.

The performance of the generated fabric was measured in terms of solar
exposure of the street level and building facades, as well as in terms of wind
flow. In each location, a different climatic goal was determined, according to
the local climate. In Stockholm, for example, solar exposure was to be max-
imised and wind flow minimised throughout all seasons, while in Seville, the
reverse goals were applied. In New York, solar exposure was to be maxim-
ised in winter, while minimised in summer, and wind flow minimized in
winter, and maximised in summer.

3.1. GENERATIVE TOOLS: AN URBAN GENOME

In order to control variations of an urban fabric using a coded simulation, it
is necessary to abstract the geometry of the neighbourhood into a set of nu-
meric parameters which the genetic algorithm can manipulate and evaluate
in a relatively short time. As a first step towards this parameterization, the
main existing traffic routes entering into each neighbourhood are catalogued
and given indexes. Once the main points of entry are identified, the street
pattern can be adjusted by choosing to place a main street between one of the
entrance points to any of the other points surrounding the neighbourhood.

The secondary street network is then determined by dividing the area be-
tween the main streets into blocks. This division is controlled and adjusted
by changing the ratio between the length and width of the subdivided areas
and the minimal subdivision area. The simulation is configured so that these
ratios and areas range over values catalogued in neighbouring fabrics. Street
widths are assigned to the resulting network according to a connectivity
analysis of the resulting fabric, using widths that are typical to the existing
urban fabric.
After the network has been determined the heights of the buildings on each side of the street can be described by grouping the streets according to their compass orientation and dividing the total available building mass to the different groups, using sections typical to the existing fabric.

The representation of this process within the simulation is based entirely on numeric data. This type of numeric representation enables a genetic algorithm to create permutations of a fabric by changing the numeric values that represent its geometry, and evaluating the results of this manipulation.

3.2. EVALUATION TOOLS

In order to create a good estimate of the solar exposure in the urban scale, an abstract street canyon model based on Robinson (2011) can be implemented in the code. Using the abstract values of local solar angles during the year, street width, facade height and compass orientation, it is possible to achieve a rough estimation of the amount of solar exposure the streets and facades receive during daylight hours. Although running almost instantaneously on fabric samples of virtually unlimited size, this method provides results that are surprisingly accurate and almost identical to the full-solar access analysis performed by professional software such as Ecotect.

Another important parameter for climatic evaluation is the average rate of wind flow on the pedestrian level of the street. While this parameter can be evaluated using a Computational Fluid Dynamics (CFD) analysis, this type of simulation typically requires a relatively long running time. In order to
minimize the runtime of the genetic algorithm it was decided to pre-analyse a set of street sections of varying heights and widths using WinAir CFD and store the results in a library which the genetic algorithm could access. Based on observations by Nakamura and Oke (1988) and Erell, Pearlmutter and Williamson (2011), the local street canyon morphology is one of the most important factors in determining the local wind regime. As the Galapagos simulation was coded to generate only sections typical to the local urban landscape, it seemed plausible to use these pre-calculated simulations to predict the wind flows of large tracts of urban fabrics. When comparing the results predicted by this algorithm with a different WinAir CFD simulation within an entire neighbourhood it appears that the results are comparable, with an error margin of 15-20% between the simulated and predicted flow rate.

3.3. SIMULATION RESULTS

At each step of the Genetic Algorithm, the Galapagos engine used the genome described above to generate 50 different samples of urban tissue. The abstract geometric properties of the samples were fed into the evaluation tools and each sample was assessed in less than three seconds. This speedy generation and evaluation process allowed the Genetic loop to run in excess of 100 generations over the course of a single night and produce results that showed a significant improvement in the measured parameter.

Fig. 2: Progression of genetic algorithm minimising street level summer solar exposure

This process was repeated for each sample, weighting the fitness criteria of summer and winter solar exposure as well as wind flow according to the desired effect across each city sample. The generated tissues were compared to the original fabric of the neighbourhood using independent evaluation tools such as Vasari, Ecotect and Winair, which all showed favourable results. The Brooklyn sample proved to be the most improved due to a significant difference in the wind regime between the summer and the winter. In
that sample the results produced by the GA show a simultaneous 25-35% improvement across all of the measured criteria. This type of achievement is very hard to reproduce by traditional "manual" methods, validating the use of these types of algorithmic tools for multi-parameter optimisation.

It is important to point out that at each site; the algorithm used a setup that was tailored to its surroundings in terms of parameters such as existing road layout, street widths, typical sections, and densities. As a result it produced fabrics that in addition to being environmentally optimised also displayed a similarity to their local urban context. It is the opinion of the authors that the ability to adapt the algorithmic results to the existing architecture is crucial from both the climatic and the social viewpoint, without which the whole exercise loses its validity.

4. Case Study II: Multi-Scalar Optimization

The Fort Greene neighbourhood in Brooklyn was chosen as a sample for a further simulation, working from the scale of a neighbourhood down into individual buildings. At this "block scale," different evaluation criteria can be used: a more precise solar access calculation, and an Energy use estimation amongst others. The new evaluation criteria required additional geometric information that has not been described in the first set of algorithms. As the genetic process progresses, the geometric model is refined and the output starts to take the shape of individual buildings, "carved out" from the abstract block massing resulting from the previous level.

4.1. BLOCK GENOME

In the block scale, the starting point of the simulation is the border of the block and the heights of its facades, derived from the urban scale results. In order to differentiate building typologies within this abstract representation,
the blocks are divided into segments describing building plots, each with a different amount of open space. Each plot can then be further refined by changing the offset distance of the building line from each of the plot borders, while keeping the open area at a fixed ratio. Thus, it is possible to distribute a certain amount of open area throughout the block in an almost infinite number of ways, effectively creating a parametric representation of building typology.

![Fig. 4: Block Genome](image)

### 4.2. EVALUATION METHODS

Since the amount of data in the block scale simulation had been significantly reduced from the larger neighbourhood scale, it was now possible to use the widely accepted ray counting method for assessing solar access by testing the obstruction of solar vectors at different times. These results were then factored with constants relating to diffuse solar radiation at the site according to the time of the year (Mardalevic, 1995) to produce an accurate assessment of daily insolation, which can be directly linked to the energy consumption of a building mass.

An equation describing a building’s Net Heat Transfer was then used to evaluate the effect of the geometry of a building mass on its energy use. This equation considers wall construction, surface area, solar insolation, volume and glazing percentage in a given climate and uses them to determine the requirements for the building’s HVAC systems for indoor temperature control, which are said to account for 50% of the energy consumption (Jones, 2008). The results from this equation were compared with the results of the Vasari energy calculation for 20 different building models. While the actual values of the results differ between the tools, the inclination of the results shows the same trends in both types of analysis. Therefore it was deemed suitable for
use, in order to determine the comparative performance level of various buildings.

4.3. SIMULATION RESULTS

Using the refined generative methods and evaluation tools, a Galapagos simulation was performed, optimising parameters such as open space solar access, winter facade insolation, and building energy use. The results were compared with blocks existing in the current Brooklyn tissue and were shown to achieve improvements of up to 25% in a single parameter, and up to 20% when performing multi-parameter optimization.

Additional fitness criteria such as: Sky View Factor, Passive Zone Ratio, Connectivity and Privacy of the outdoor spaces were also implemented into the simulation, but will not be expanded on in this article. Finally, it became possible to direct a genetic simulation using a weighting function for the different evaluation criteria in order to control the evolution of an urban block towards a certain climatic goal.

4.4. EMERGENT PATHWAYS

A surprising feature of the simulations described above is the ability to run them simultaneously on several blocks within a fabric. Using the urban scale optimization results of several adjacent blocks as a starting point, the algorithm was able to further optimize up to four blocks at a time, weighting factors such as open space solar access and connectivity as well as building energy efficiency. By using repetitive optimization of congruent patches of different blocks, a network of pedestrian pathways began to emerge, achieving an urban fabric in which building typologies truly respond to their
neighbours. Collectively adapting to both the climatic conditions as well as the architectural environment, the buildings function better as a whole than as individuals.

5. Conclusions

One of the well-known problems of using a genetic algorithm within the design process is runtime. The experiments addressed in this paper confront this problem by keeping the geometric rules of the generative processes as simple as possible, and by finding abstracted estimation methods for the evaluation criteria utilized. By parametrically implementing architectural concepts such as plans and sections, a meaningful discourse with the design practice is achieved and the genetic algorithms presented can become useful tools, enabling designers to achieve urban plans with added performative value.

A recurring objection against parametric design is that it often results in generic architectures which do not interact with the built fabric surrounding them. In this paper it was shown that if the architectural qualities of the built environment are quantified and introduced into a generative system, it is possible to produce geometries that relate to their neighbouring buildings, creating a seamless connection between the fabrics.

The method this paper has developed shows a potential for integrating various climatic principles relating to energy use and to pedestrian thermal comfort into the architectural design process. It is suggested that the designer control the process by determining the importance of different parameters in
the genetic algorithm. The evaluative nature of this method would eliminate unsuitable typologies at the outset of the design process, leaving the architect with only "good" options to choose from. These results can now be used as planning guidelines to assist more traditional architectural practice.

It can be said that this series of experiments show considerable promise for further study. As actual improvements were reached at many scales and across a number of criteria, the generative-evaluative loop of the genetic algorithm seems to be the appropriate framework in which to place this discussion. As the computational horizon expands, more and more variables will be able to be integrated into the equation, and detailed architectural solutions may be achieved.

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