Climatic Formations: Evolutionary Dynamics of Urban Morphologies

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Abstract

In recent years, sustainable design methods have become a major concern within the building industry. There is also a growing awareness of the impact urban morphologies have on the overall energy and fuel consumption of a city. This paper investigates digital form-finding methods for generating an urban tissue to suit climatic conditions. In this research, a cascading series of genetic algorithms at multiple scales is coupled with environmental evaluation methods as fitness criteria. The methods devised in this paper integrate evaluation tools written with an object-oriented scripting language together with the Galapagos genetic solver in the Rhino/Grasshopper/Python platform. It is shown that the developed methods can be used to create large-scale urban layouts with improved street-level climate conditions as well as aggregations of buildings that function together to improve environmental and architectural parameters. The methodology developed in this paper is tested on a site with an area of approximately 1 km^2 in Brooklyn, New York, chosen because its climate features a large yearly variation in temperature and wind regime. The existing surrounding urban fabric, along with the local climatic conditions, is taken as the initial input in order to develop algorithmic processes with sensitivity to the site context.

Keywords: urban fabric; climatic optimization; multi-objective optimization; multiscalar; genetic algorithm

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1. Introduction

In practice, the development of an urban tissue typically occurs in separate phases at several different scales and is described in terms of separate projects, such as the master plan, detailed master plan and building design. In urban scenarios dealing with multiple scales, decisions suited to one scale might have an unfavourable effect on others with respect to microclimatic conditions. The climate-adapted urban process should therefore aim to integrate the different scales—urban, block and building—in order to allow for control not only of the behaviour of the buildings themselves, but also of the nonbuilt spaces between them.

In contemporary architectural practice, many digital tools have already been devised to quantify the performance of a building in its environment. However, these tools are typically used in a posteriori analysis of the architectural design, that is, to evaluate preconceived design alternatives, rather than as integrated processes to generate design options. This study focuses on form-finding methodologies for generating an urban fabric that can utilise environmental analysis as a driver for the creation of forms, with the objective of improving the urban environment's microclimatic conditions. In this paper, genetic algorithms serve as the computational framework for a consideration of multiple evaluation criteria to determine the fitness of an urban morphology at multiple scales. The research methodology represents an attempt to create an integrated digital workflow on a single computational platform that uses a genetic solver together with customised evaluation tools for designing an urban fabric.

In the following sections, environmental criteria such as solar access, wind flow and energy consumption are used as fitness criteria along with other architectural parameters. These customised evaluation tools use simplified calculation methods to account for the runtime of the algorithms and are written for the Rhino/Grasshopper/Python computational platform. The results of the algorithms produce street-grid layouts, public open-space distribution, building masses and facade surfaces that are adapted to their local climate. The correlations of the design elements in the urban settings are considered in forming the overall algorithmic process, which comprises a cascading series of genetic algorithms. The resulting morphology of the algorithms presented in this paper is compared to the existing urban fabrics of their respective sites. In this comparison, the result of the design experiment

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showed improvements in the majority of the criteria, suggesting an overall improvement while maintaining an architectural similarity to their surroundings.

2. Theoretical Background

2.1 Urban Scale

According to Salat, unsuitable urban morphologies can double the energy consumption of urban tissues. In support of his view, an analysis of multiple cities, such as London, Berlin, Toulouse and Paris, has been carried out by research undertaken at MIT in collaboration with the University of Cambridge and at the Centre Scientifique et Technique du Batiment in collaboration with the Atelier Parisien d'Urbanism. Both studies draw the conclusion that certain urban textures can reduce the energy consumption and carbon emissions of a city, confirming the importance of the morphology of urban fabric to sustainability. These findings indicate the importance of understanding the potential of urban forms for climatic control. However, Adolphe (2000) has noted that it is difficult to evaluate the effect of urban configuration on outdoor climatic conditions and the energy balance of a building due to the extreme morphological heterogeneity of urban contexts. Adolphe proposes a set of morphological parameters including, among others, rugosity, porosity and sinuosity as three-dimensional geometric abstractions to measure wind flow around and solar access and energy balance of buildings. Moreover, research conducted by Kakon and Nobuo shows the correlation between pedestrian comfort and the street canyon, where they employed street sections as geometrical abstractions of urban forms. The present study adopts these principles of geometrical abstraction to integrate them into a process used to generate urban forms. The research described above shows that processing the amount of data needed to describe a large area of urban fabric is a challenge that needs to be addressed by using methods employing a set of geometric abstractions.

2.2 Architectural Scale

Historically, the building envelope has had multiple aesthetic and functional design implications, and one of these is the function of climate control. Today, software helps designers simulate the heat and airflow around the building envelope, and they can use this information to improve the performance of the design. The two main concerns for designing a building envelope with passive design principles are the form and materiality of the building. The general massing, locations and sizes of the openings on the building envelope have a strong influence on the building's daylight quality, solar heat gain and heat transfer, all of which are directly related to the building's energy consumption.

Masdar City in Abu Dhabi, designed by Foster + Partners, is recognised as a precedent for a design approach that integrates urban form with individual building scale. In Masdar, the street arrangement has a southeast/northwest orientation with a staggered grid to maximise the self-shading capability of the buildings. In addition, the materials with which the buildings are clad help to minimise heat gain in the streets due to reflected radiation. It is suggested that this multiscalar approach, combining the orientation of the urban grid, the massing distribution of each block and the effect of the building envelope on both its interior and the street, represents a direction for further exploration of the correlations of the different design elements considered at each scale.

2.3 Genetic Algorithms

An emerging discipline in architecture is the use of computational genetic algorithms (GAs) to solve design problems. GAs are modelled on the evolutionary process of natural selection to search for a fittest individual according to set criteria by repeating the four phases of initiation, selection, crossover, and mutation (Kim, 2012). The advantages of GAs and their ability to search through a vast design space for a solution have been noted by numerous scholars.

Furthermore, GAs have an inherent ability to integrate simulation tools as a part of the optimization process, and when considering multiobjective optimisation, they can demonstrate the results of the trade-off of different criteria (Caldas, 2003). These advantages make optimisation routines using GAs a desirable form-finding method for performance-driven solutions that rely on simulation tools. GAs are now becoming a more common form-finding tool in architecture, where practices such as SOM use GAs to find the optimal solution for daylight quality, structural efficiency, construction cost, view quality, carbon footprint, acoustic quality, programmatic compliance, etc. The availability of user-friendly evolutionary engines, such as Galapagos in the Rhino/Grasshopper environment, encourages designers to utilise GAs as a part of their design process. This tool vastly simplifies the writing of a GA and enables the seamless integration of the generative process with the analysis process. Despite these advantages, GAs also have some known problems, one of which is the relatively long runtime of the algorithm, which results from the time it takes to evaluate every single individual within a population. Integrating the simulation tool with the genetic engine is greatly limited by computing power, and in many cases the simulation tool needs to be simplified in order to provide real-time feedback.

3. Methods

This section discusses the overall algorithm and focuses on the measures taken in developing the customised evaluation tools. In the experiment described in this paper, the urban context is broken down into urban, block and architectural scales, and each scale is addressed with a GA with multiple fitness criteria. At each stage, the border of the site is considered a part of the generative input for the simulation. Starting the process with the larger scale therefore allows the information to trickle down, informing all the possible results with data acquired in the earlier stages.

The algorithms for producing geometric models at different scales and the tools used for determining fitness criteria were written by the authors as customised evaluation tools. They were designed to be suitable for the operation of a GA within the limits of the computational framework of a laptop. The experiments investigated different evaluative strategies to be considered at different scales based on the geometric data to be processed. Different evaluation criteria were considered to determine fitness at different scales. A total of 10 evaluation criteria were considered in the experiment, each of which were translated into customised tools. The criteria were park influence, wind flow, winter solar exposure, summer solar exposure, porosity, passive zone, connectivity, heat transfer, sky-view factor and reflection. Of the customised evaluation tools, solar access, wind flow and energy consumption are further discussed in this section. Two main requirements were considered when writing these simulative tools: confirmation of results against existing software tools and a runtime efficiency enabling rapid numerous iterations. These methods took advantage of the use of different scales in the simulation, resulting in an analysis that was sufficient to describe the current levels of abstraction.

Two methods were developed for use at different scales to calculate solar radiation. For the urban scale, this study adopted an abstract street-canyon model from Robinson (2011). This model relies on the angle of abstract facades or streets relative to the north and the height and distance of obstructions to quickly calculate an estimate of their solar exposure over given time periods. This method lacks accuracy in comparison to other types of measurements, with results describing only the percentage of time a surface is exposed to direct sun. However, it is extremely efficient, because it is based on abstract trigonometric calculations and can be performed on a database by describing solely the street width and the angle and height of the two facades, without resorting to actual modelling.

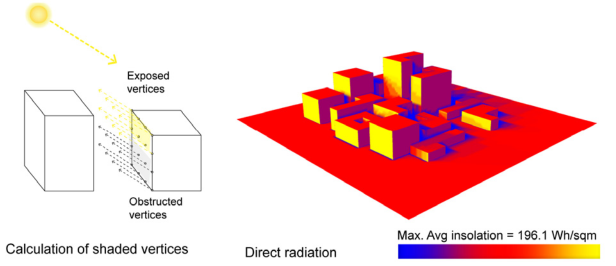

Fig.1. Ray Counting Method for Solar Radiation and Result of GhPython Script

On a smaller scale, this study implemented the widely accepted ray counting method, testing the obstruction of solar vectors at different times as well as the reflection of the same vectors. The results of these tests were then factored with constants relating to diffuse solar radiation in the site according to the time of the year (Robinson, 2011).

Both methods were calibrated by testing a group of 20 models against the Ecotect solar radiation tool, and they show similar values and tendencies, validating their use in the generative algorithm.

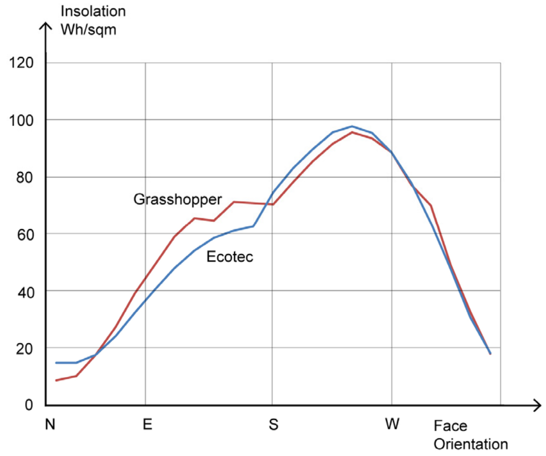

Fig.2. Solar Radiation Result Comparison of GhPython Script and Ecotect

CFD analysis of urban fabrics is extremely time consuming, taking up long periods of calculation in any of the prevailing software packages (such as Winair and ANSYS). Alternatively, different abstractions of the urban fabric were attempted by the authors to enable predictions of wind flow without resorting to actual simulation.

In view of the fact that the geometry of the street canyon has a large effect on the flow and turbulence patterns of the wind (Nakamura and Oke, 1988), it can be seen that typical street sections have typical flow patterns (Erell, Pearlmutter & Williamson, 2011). A hypothesis was formulated that the average rate of wind flow on a given street has a good correlation with the relation between its width, height (on both windward and leeward sides) and length and its angle to the wind. In order to test this hypothesis, a series of CFD simulations was performed on models with different height parameters (which can appear on each side of the canyon), different widths and 15-degree variations in the wind direction.

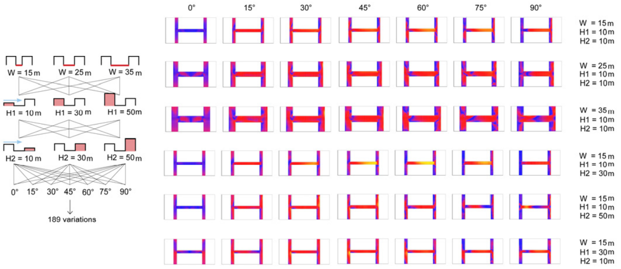

Fig.3. Examples of Wind Simulation Library Samples

The results were stored in a library and then used to predict the wind behaviour of all the streets of a neighbourhood-scale fabric. In this specific experiment, the library took into consideration the morphological characteristics of the existing site conditions preselected for the experiment in Brooklyn, New York, before determining the range samples for street-aspect ratio and wind direction. The library samples included a building-height range of 10-50 m and a street-width range of 15-35 m. For all the morphological variants, the possible wind angles were measured at every 15 degrees, and the results were added to the library for reference. The combination of the ranges of the width and height together with the varying angle of the wind provided 189 variations, which were stored in the library for the initial experiment. When these variations were compared to a Winair simulation of the same fabric, it was shown that a strong correlation in the tendency of the results could be expected, especially if the dimensions of the streets of the tested fabric were similar to those in the library. Because the CFD simulations contained in the library can be performed in advance, the library is theoretically unlimited in the amount of samples it can contain, and its accuracy will increase in direct relation to its size.

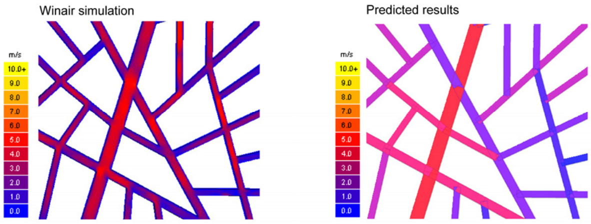

Fig.4. Result Comparison between GhPython Script (right) and Winair (left)

For an energy evaluation tool, the widely accepted calculations of building net heat transfer can be considered part of the equation to relate the form of the building and the build-up of the building envelope (Jones 2008). This method includes elements such as wall construction, surface area, volume and glazing percentage as well as the heat generated from building usage and solar heat gain. Net heat transfer was used to approximate energy consumption in this project, estimating trends related to geometric form and massing.

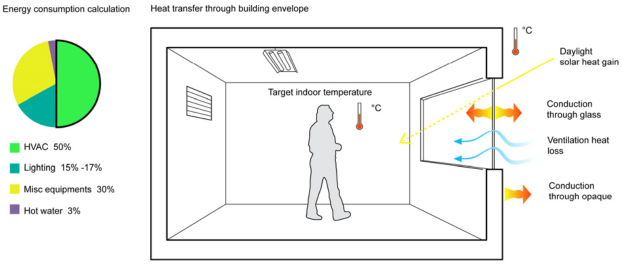

Fig.5. Heat Transfer Diagram

Because only a portion of the full energy calculation was employed, it was necessary to compare the results of the evaluation tool to those of a validated tool such as the Vasari energy calculation. A total of 20 individual forms of varied shapes and sizes were evaluated with both the Vasari software and the evaluation tool included in Grasshopper. It was clear from the graphs and the table that although the numeric values of the results differed between the tools, the inclinations of the graphs showed the same trends in both types of analysis. Although a precise prediction of the energy consumption was not achieved, it was possible to use this method to compare different forms and identify those that are preferable in terms of energy use.

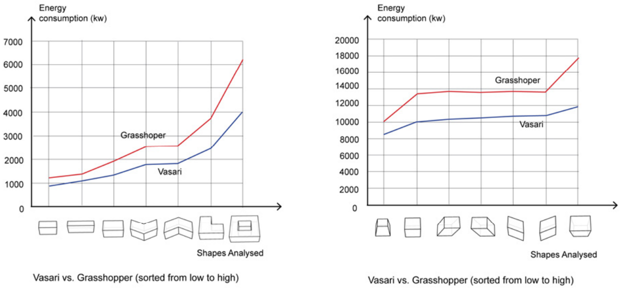

Fig.6. Result Comparison between GhPython Script of Heat Transfer and Vasari Energy Simulation

As further evaluative tools, additional parameters were encoded into the Rhino/Grasshopper/Python environment. Passive zone ratio, the first of these parameters, is an offset from the building envelope, usually double the net floor height in size, which is said to be the maximum depth at which natural lighting and ventilation can be utilised. Additionally, sky view factor (SVF) was used to describe the cross-sectional proportions of street geometries. It was employed to describe the amount of sunlight gathered and the amount of long-wave radiation released into the atmosphere, both of which affect the urban heat island. At the building scale, it is an indication of the daylight potentially available at each point in the building's facade. In order to calculate this parameter, an upper hemisphere of light rays is generated at each vertex of the building's surface and the intersections of the rays with the surrounding environment are calculated.

4. Case Study

New York City was chosen as a test site because it has a relatively extreme climate—cold and windy in the winter, hot and balmy in the summer—and because it displays a differentiated wind regime from season to season, providing rich ground for climatic optimisation. In addition, the published documentations of New York City allowed for thorough research into existing local typologies and served as a basis for comparison to the resulting fabric.

The Fort Greene neighbourhood in Brooklyn was chosen as the urban tissue sample, because it has medium-to-high density with both low- and highrise typologies and a mixed residential/commercial programme. The specific area chosen for this experiment was surrounded by different grid layouts and could potentially bridge them in several ways. A 1 km^2 area, although not empty, was taken as a site to provide an experimental setting, and its existing tissue was used as a sample to determine programme, density, typical sections and block typology. Existing connections with the neighbouring areas were considered starting points for the street layout. The results were always compared to this tissue in order to accurately quantify improvements over the existing situation.

In order to generate an optimised fabric using a GA, it was necessary to couple the analysis tools mentioned above with a genome set that can describe urban geometry. This can be achieved by abstracting the geometric shapes that make up the fabric of a city by using the architectural concepts most relevant to the scale at hand.

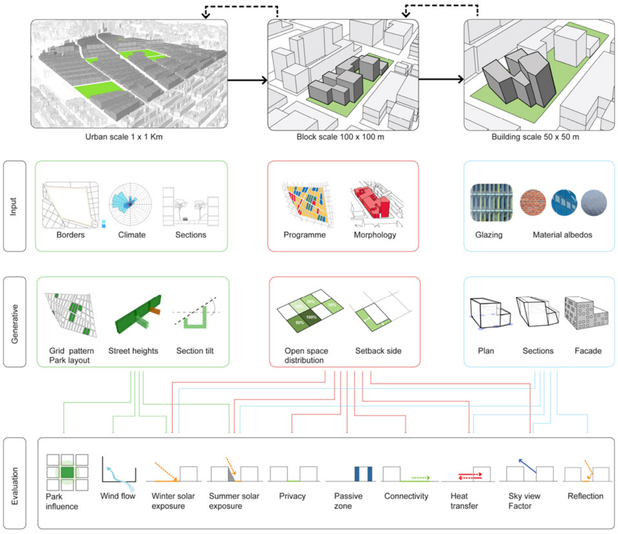

Fig.7. Overall Algorithmic Process in Three Scales

Considering the orthogonal street layout of Brooklyn, a street could be defined simply as a line between two source points. By parameterising the source points of the main streets of an urban patch, a large variety of main street configurations could be described. The source points were considered the genome for a GA. Further subdivisions were made based on the configuration of the primary streets by recursively subdividing the initial grid with a set ratio of potential block width and length. The proportion of the blocks was again determined based on the local urban morphology, which showed a length-to-width ratio of 1:2 and typical block sizes around 200 m^2. For the primary and secondary street network, the actual street width was determined according to the centrality of the street as defined by a space syntax analysis, with streets increasing in width as their centrality increased. The geometry of the streets was described by a series of typical sections comprising the street width and two height parameters at either side. The height and width ranges were taken from measurements in the existing urban fabric. The aforementioned ranges of 15-35 m for the width of the streets and 10-50 m for the height of the buildings were used in the experiment to generate the street sections. By grouping streets according to their angle relative to the north and assigning heights to each of these groups, it became possible to run a genetic simulation that distributes a set built volume onto an urban patch while optimising criteria such as facade solar exposure and wind flow. It was thus possible to run a GA while maintaining key architectural attributes by placing constraints on variables such as street width and facade height, which derived from the studied site. The benefit of using a GA was clearly demonstrated by running a simulation with multiple, conflicting evaluation criteria. It was shown that in comparison to the existing fabric of Brooklyn, a 25% higher facade exposure to the sun in the winter months could be achieved, and average wind flow could be decreased in the winter by 35% and increased in the summer by 17%.

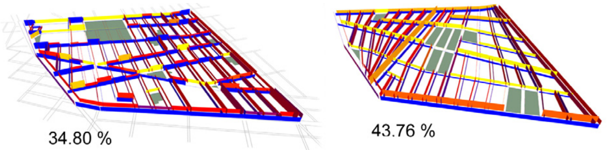

Fig.8. Percentage of Daylight Hours Exposed to Direct Sunlight. Existing Fabric (left) and Urban Scale Result from Algorithm (right)

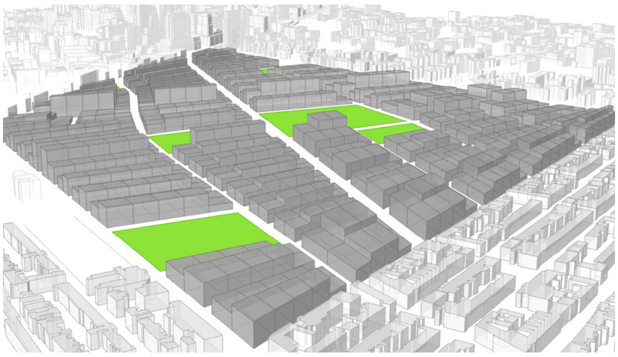

Fig.9. Urban Scale Algorithm Result

At the block scale, it was possible to quantify the geometry of a typical Brooklyn block in a similarly abstract fashion. Deriving the border of the block and the heights of its facades from the urban-scale results, it was possible to describe different typologies by dividing the block into segments and controlling the - offset distance of the edges of each of the segments from their respective borders. For example, a courtyard typology could be described as an offset of all the centrally facing edges towards the circumference of the block.

The percentage of open space of the existing urban block could be defined as a used input. The analysis of the existing urban fabric of the chosen site showed an average of 30% open space within each block, which was later used in the simulation. The number of subdivisions of building plots was also measured from the existing site, and an average of eight building plots per block were assumed in the experiment. Similarly, based on the existing height range in the site, the range of building heights used was 10-50 m.

Seven fitness criteria were used to generate the block morphologies. At this scale, a more precise solar calculation (ray counting method) was used to determine the winter and summer solar exposure and was combined with other environmental parameters including energy use, SVF and passive zone ratio as well as architectural parameters such as the connectivity and privacy of the outdoor spaces.

The weighting the different fitness criteria became a critical factor in the genetic simulations, with different ratio of the weightage of the fitness criteria leading to varied morphological results. The differences in the weightage of the fitness criteria were influenced by the programme. The blocks were divided into two main programmes, residential and commercial. In order to determine the correct ratio, existing blocks were measured with respect to the analysis criteria, and it was observed that different building functions exhibited what can be described as typical weighting patterns. For example, in the Brooklyn area, residential blocks show a strong emphasis on passive zone ratio and open space privacy, whereas commercial blocks have a lowered net heat transfer and an increased SVF. Thus, it was possible to calibrate the GA to achieve blocks with properties similar to a typical commercial, public or residential block from that area, while achieving better scores in most of the measured criteria. An improvement of up to 30% could usually be achieved in the three or four parameters given the most weight in the fitness function, without significantly decreasing the score of the other criteria.

An important aspect of this type of simulation is that several adjacent blocks can be optimised simultaneously to achieve a result that is both better in terms of environmental criteria and shows emergent patterns of public networks between the blocks. In this way, the fabric can be worked on in patches; the different patches can be stitched together by rerunning the simulation on the patch borders, thus achieving a well-knit fabric with different networks distributed across the different scales.

At the building scale, it was possible to rework the geometry of the resulting blocks, using another round of GA simulations to refine the buildings in terms of plans, sections and elevations. In this round of simulations, only blocks that exhibited low values in some of the parameters were chosen as starting points.

The corner points of the building massing were taken as the genome to modify the massing of the block without deviating more than a set tolerance from the initial volume. For this experiment, each vertex describing the block geometry was able to move in x and y directions freely, with a maximum range of 4 m. The glazing percentages of the building facades were used as another genome set in order to further optimise the energy consumption of the collection of buildings within the block. The glazing percentage ranged from 20 to 100%. The facades were divided according to different elevations of the massing, and each elevation was further subdivided every 10 m, allowing the algorithm to assign different glazing percentages for different building heights as well as for elevation.

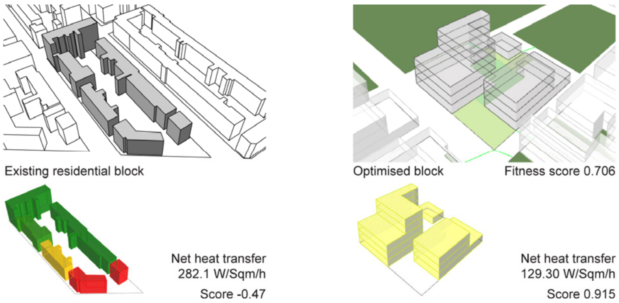

Fig.10. Existing Fabric (left) and Urban-Scale Result from Algorithm (right)

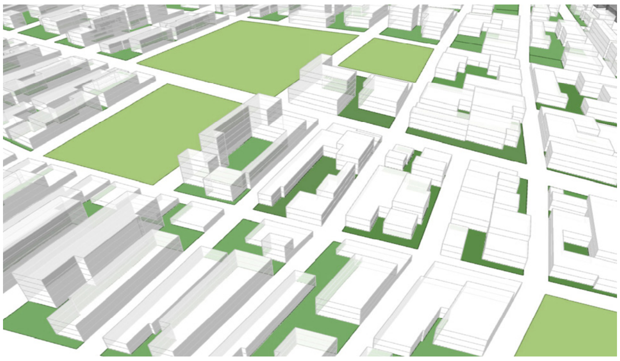

Fig.11. Urban-Scale Algorithm Result

The objectives for optimisation at the building scale varied according to the assessment of the result of the previous block scale. Therefore, the conditions used as fitness criteria varied accordingly for each block. Although specific algorithms can be shown to improve properties such as energy use of buildings, they can also be tailored to improve microclimatic conditions of the surrounding public spaces. For example, they can be tailored to improve the quality of shared open space by maximising solar access for winter, minimising heat gain during summer, improving SVF and reducing the reflected glare of a glass facade on the street level.

Combined, these experiments form a holistic approach to urban design, passing data sets from one scale to the other and insuring a continuous improvement of the generated fabric. Because they can be performed on a single platform, they enable designers to make informed decisions at each of the different scales and to see the effect of the scales upon

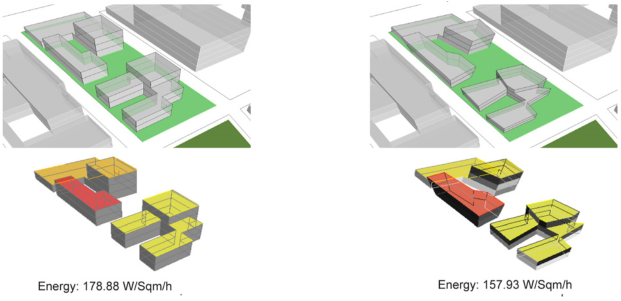

Fig.12. Output of the Block-Scale (left) and Urban-Scale Results from Algorithm (right)

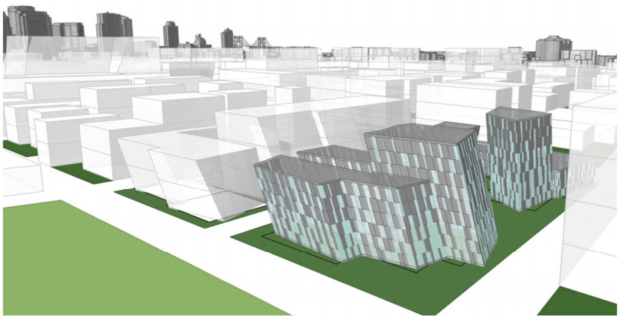

Fig.13. Building-Scale Algorithm Result

each other. The GA together with the framework of the aforementioned experiment provides several solutions at each scale level, allowing designers to intervene and consider other design criteria to choose from alternatives which provide design options that consider climatic aspects.

5. Conclusion

In this design study, the applicability of GAs to improving the climatic performance of multiscalar urban environments was tested and shown to have potentially useful outcomes. As a design tool, the methods explored in this paper are thought to be most appropriate as a part of the feasibility stage, where the procedures described can be used to quickly test different design conditions and ideas on a given site by varying density, programmes and materiality. The result of algorithms can be used to assist the decision-making process, embedding into them the environmental consequences of the design.

At the block and building scales, the method developed shows potential for integrating various climatic principles relating both to energy use and pedestrian thermal comfort, which is rarely experimented with. Not only can individual blocks be optimised, but whole areas can be developed simultaneously, with the built masses in different blocks functioning together to achieve a result that could not have been achieved individually.

The evaluation criteria considered in this paper form only a portion of all the considerations, criteria and requirements that need to be met by an architectural or urban project. Only a handful of the most relevant evaluation criteria were selected in order to study their relationship with designed forms at the different scales. To further enrich the solution, other architectural criteria were introduced as part of the evaluation for the different scales. In some places, a designer's decision will surely be required when determining the priority of different criteria as well as in assessing the outcome of the algorithm and choosing between the different results.

In order to be used for a real project, the evaluation tools described in these experiments need to be refined to improve their accuracy. The wind evaluation tool, for instance, has inherent limitations as it estimates the outcome by looking at the proportions of geometry in localised areas and predicting the combined global results. However, the accuracy of this estimation could be greatly improved by expanding the sample library with further case studies, including varying border conditions. In order to improve the accuracy of the net heat transfer tool, it would be feasible to add a library of different wall constructions and the heat generated from different usages of the building, as well as other criteria taken into account in a full energy calculation.

In the architectural paradigm, there are several ways to approach the different design issues tackled in this study. The reflection and the albedo level addressed at the building scale could also be dealt with using the materiality of the finishes instead of adjusting the form as suggested in the experiments. The generative methods for all the scales tackled here are based on simple geometric rules such as subdivisions of lines, offsets and displacements of points and curves. These methods of generating geometries are sufficient for this particular set of experiments. However, these geometric rule sets are limited in what they can produce. For instance, these methods would not be appropriate when applied in a context with curvilinear street layouts or staggered grids. Another feature that could be implemented at the building scale is a staggering of the facades into porches and terraces.

Similar simulations could be run in other places in the world. In order to apply the design methods described in this paper in other locations, two main alterations will need to be made: expansion of the morphologies contained in the library for wind simulation and establishment of a geometric logic to generate the forms. The tools that rely on equations or specific calculation methods, such as solar access, energy and SVF, could be used to reproduce the experiments in other contexts. However, further assessments are required to determine the geometric logic that could be applied in different city contexts. The use of source points, offsets and vertexes as genomes could still be valid if the intended results of the morphologies are noncurvilinear. The ranges of the height and width of the streets and of building height need to be determined by users prior to running the algorithm. These height and width ranges need to be reflected in the library of the wind simulation. It is also required that users have a prior understanding of how different weights for multiple fitness criteria can be distributed to suit the climate and required function. Given that these alterations and modifications are considered, it will be possible to employ methodologies described in this paper and these types of experiments in other locations with different climatic conditions.

Although the issues raised here represent challenges and many improvements can be made to the system, the results of this series of experiments are promising. As actual improvements were made at many scales and in many criteria, the generative-evaluative loop of the GA seems to be the appropriate framework for this discussion. As the computational horizon expands, more and more variables can be integrated into the equation, and detailed architectural solutions may be achieved.

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