Research Article

IJAC

International Journal of
Architectural Computing
1–31

DOI: 10.1177/1478077118777236
journals.sagepub.com/home/jac
SAGE

Evolutionary algorithms for generating urban morphology: Variations and multiple objectives

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Abstract
Morphological variation of urban tissues, which evolve through the optimisation of multiple conflicting objectives, benefit significantly from the application of robust metaheuristic search processes that utilise search and optimisation mechanisms for design problems that have no clear single optimal solution, as well as a solution search space that is too large for a 'brute-force' manual approach. As such, and within the context of the experiments presented within this article, the rapidly changing environmental, climatic and demographic global conditions necessitates the utilisation of stochastic search processes for generating design solutions that optimise for multiple conflicting objectives by means of controlled and directed morphological variation within the urban fabric.

Keywords
Architecture, computation, evolution, biology, urban, variation, morphology, genetic algorithm, computer aided design

Introduction

Variation of blocks and superblocks increases the potential for the urban fabric in which they are embedded to adapt to changes in environmental and climatic conditions and helps to construct patterns of spatial differentiation that are identified with the perception of urban culture and qualities that make a city a good place to live. The Universal city beloved of the early 20th century Modernists has been built everywhere, and all too frequently simply comprises a uniform array of a single block type distributed across a grid, with little if any adjustment to specific ecological or environmental contexts. Today, rapidly changing climatic conditions and the exponential growth and mobility of populations are accelerating changes to the environmental context of many cities across the world. However, there are some cities that evolved over many centuries that have adapted over the course of their history to changes in their environment and climate; surviving and continuing to grow over several centuries within their environment (Figure 1).

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Figure 1. Listed by UNESCO as a world heritage site in 1981, the oldest part of the city of Fes in Morocco; Fes El Bali is distinctive in its continued preservation of its ancient urban configuration. For the purpose of the experiments presented, the block was modified to allow for upper level connections.[1]

However, changing the built forms and spatial patterns of a city is a slow process. In the past, there have been some cities that have been able to adapt to different climatic conditions at a rate relative to the rate of change in their context. However, the rate at which the climate is predicted to change over the next 50 years is accelerating; as such, it is widely thought that there is insufficient time available for mature cities to adapt.

The challenge lies in developing a computational process that is capable of generating urban morphology that is optimal for multiple conflicting objectives. One widely used approach to multi-objective computation is for the designer to give greater weighting to one objective over the others, or to vary the reactive importance of the objectives in a cascading rank. This makes the process deterministic on the initial conditions and decisions of ranking. What if the initial conditions were to change during the computation?

It is possible to incorporate a feedback control operation that modifies itself through time as it converses with a continuously shifting landscape, thus maintaining an equilibrium state when met with continuous change.[2] Natural biological evolution offers a model of a system in which populations have adapted to changing environmental and climatic conditions without direction or designer bias. Precedence for the application of an evolutionary model as a problem-solving strategy dates back to the early 20th century. It has since developed into a model that has been applied in a multitude of different fields to provide solutions to problems that required objectivity, optimality and efficiency. Experiments presented within this article address the issue of generating urban morphological variation evolved in response to conflicting criteria through the modelling of urban form by means of a multi-objective evolutionary approach.

Variation and adaptation

The biological model

The significance of genetic diversity within a population has been documented to contribute to increased adaptability to changing environmental and climatic conditions as well as heightened fitness levels across generations. A population that has evolved within any particular environment will have the majority of its individuals close to optimal fitness, but will also have a significant fraction that are genetically and morphologically different, or varied, from the norm, and so are less ‘fit’. When environmental and climatic conditions change, those formally optimal or ‘fittest’ individuals will now be less fit for the new conditions, but among the formerly ‘less fit’ individuals there will be some that are better matched to the new conditions, and so they become the new ‘fittest’. They will prosper and over time their genes will propagate through the population until they become the dominant gene set. It has been argued genetic diversity in a population is significant in three ways: ‘The importance of species diversity for ecosystem functioning; the importance of genetic diversity to predict the vulnerability of a species to extinction; and the importance of genetic diversity for survival of populations within a species’.[3] Each of the three is interdependent on the level of fitness – both individual fitness and fitness of the population as a whole.

However, Schemske et al.[4] and Lande[5] argue that the contribution of genetic variation to a population’s adaptability is more evident over a long period of time and less so in the short run; thus, putting forward the notion that the effects of higher rates of genetic variation across multiple generations contribute to the robustness of a species survival in the face of environmental stress factors.

Yet, there is a central difference between genetic variation within an individual’s genome to the genetic variation between the genomes of the individuals across the population; this difference is assessed with regard to the rate of adaptation of these species to changes in environmental and climatic conditions. As the amount of genetic variation within an individual’s genome is limited (mainly to the genome’s length and inherited traits), the genetic variation between individuals of the same species occurs at higher frequencies relative to the single individual, as such Den Boer et al.[6] argue that ‘this means that a population can only achieve its adaptability by distribution of the variation across individuals.’

In addition to contribution of genetic variation to environmental adaptability, there is also an impact of environment on gene expression of the phenotype. This can enable some species to react to environmental and climatic changes without the necessity of genetic changes.[3] This is a widespread phenomenon in plant species known as ‘phenotypic plasticity’[7] and is an additional contributing factor to a population’s ability to adapt to its environment.

The urban model

The discourses of architectural theory and design knowledge are focused on the city and urban space, and the comparison of the city to a living form is commonplace. There are many disciplines and domains of knowledge that examine and reflect upon the city, and the scientific study of the city and its systems now cuts across many disciplinary and professional boundaries. They include, among many others, complexity scientists, urban physicists and climatologists, social scientists and urban geographers, economists and ecologists, systems and civil engineers, software and information/data specialists, designers of artificial intelligence and, increasingly, architects and urbanists. Over the last two decades, there has been an increase in design research driven by awareness of potential climate and ecological changes. This is reflected in the change from the close confines of the specialisms of building physics and architectural engineering to broader but still specialised programmes of Sustainable Environmental Design and Ecological Urbanism design research in academia and in practice.

There are numerous different approaches across the field, with differing design methodologies, ranging from strongly performance-driven positions predicted on the goal of efficiency to those that are concerned with social and cultural revisions to the estrangement of society from the natural world. For example, in Planning, the social sciences had long been part of the research agenda, along with comparative and systematic studies in urban morphology, and Landscape Urbanism is usually described by its proponents as integrating urbanism with ecology, landscape, infrastructure engineering with social concerns. What is common to all is the rejection of the idea of nature and artifice as being unrelated or opposed.

The Centre for Advanced Spatial Analysis (CASA) was founded in 1995 as a research centre at the Bartlett, UCL, producing a long and continuing series of working papers and books, among which Mike Batty’s[8] ‘Cities and Complexity’ was significant in establishing the application of the sciences of complexity to cities. The Santa Fe Institute was founded in 1984 to research Complex Adaptive Systems, and the study of cities as a phenomenon of the evolution of human social systems is one of their principal areas of research. There has been an increasing focus at Santa Fe to the quantification of urban dynamics and to contemporary aspects of social phenomena in cities.[9] Bettencourt's[10] more recent publication takes its title from Jane Jacob's[11] question that is widely acknowledged as the first to define the form of cities as a problem of organised complexity. Bettencourt's emphasis is on integrated social networks as the primary purpose and driver of the growth of cities, and he argues that cities make productivity gains and become spatially denser as they grow.

The literature of complexity studies of cities continues to expand and is, in the main, focused on mathematical modelling of either the allometric and morphological relations of the physical forms of cities and urban tissues such as the overall shape, compactness and density, or on the quantification of flows of energy, information and material and their associated networks. There are numerous quantitative studies of existing cities and conurbations, but their scope of work very rarely includes either analysis of a city's place in a network of other cities, towns and settlements and the ecological and climatic context in which they are embedded, or of the origins and evolutionary history of systems of cities in relation to climate and ecology.

The development of 'evolutionary' design algorithms for architecture commences with an understanding of the processes of evolutionary and embryological development that bring about the morphogenesis, variation and distribution of all living forms. Evolutionary algorithms are iterative processes that are structured on simplified logics abstracted from evolution and are commonly used in many fields for solving non-linear and intractable problems. They offer an iterative design tool for the exploration of both stable and dynamical architectural and urban forms. In order to develop and use such a tool requires a radical change in design thinking and in the process of design, a change away from the traditional process of perfecting a single unique design and towards a process of 'evolving' varied populations of context-specific architectural forms, with differing ratios of the driving parameters. The logics and techniques of a generative 'evolutionary' design system that integrates form and force through continuous iterations offers the potential of processing the flow of morphological, environmental and climatic forces through a large group of urban blocks, and balancing variations of form with the organisation and behaviour of the whole urban configuration to respond effectively to forces that would be imposed upon it in the physical world.

Evolutionary computation as a problem solver

Evolutionary multi-objective optimisation has been extensively applied as a problem-solving strategy since the late 20th century; Although the earliest applications of evolutionary principles as an optimisation process date back to the 1930s, through the work of Sewell Wright,[12] and then later more forcefully through the work of Holland's[13] genetic algorithm (GA), Rechenberg and Schwefel's evolutionary strategies (ES)[14] and Fogel et al.'s[15] evolutionary programming (EP); it was not until the 1980s that the first attempts to design a multi-objective evolutionary algorithm (MOEA) emerged, primarily through the work of David Schaffer's[16] 'Vector Evaluated Genetic Algorithm' (VEGA) where a population of individuals were selected between generations opposed to the conventional approach of single-objective evolutionary algorithms (SOEA) in which a single individual was selected to create subsequent generations.

However, one of the seminal figures in the field of MOEA, David Goldberg,[17] put forward the concept of integrating Pareto optimality and dominance as a selection strategy within an evolutionary algorithm, allowing for the algorithm to incrementally increase the fitness of the solutions for each fitness criteria independently yet avoid early convergence towards a local optimal solution. Inspired by Goldberg's research, many of the leading MOEAs of the 1990s incorporated his selection strategies, most famous were the Multi-Objective Genetic Algorithm (MOGA),[18] Niched-Pareto Genetic Algorithm[19] and the Non-dominated Sorting Genetic Algorithm (NSGA).[20]

The early 21st century witnessed a major development in MOEAs through the introduction of the Elitism Strategy, a concept primarily credited to Eckart Zitzler[21] through his algorithm titled Strength-Pareto Evolutionary Algorithm (SPEA) (the SPEA was developed into a second more robust algorithm titled SPEA-2[22]). The objective of utilising an elitism strategy (or what is sometimes called an Archive) within MOEAs is to allow non-dominated solutions to compete with individuals that lie outside of their respective generations. Zitzler's[21] concern was that although a non-dominated solution may have earned its non-dominated status within its own generation, it may also be non-dominated across multiple generations, however by not allowing it to 'survive' in order to compete with future generations, the solver may lose potentially highly fit individuals, therefore the elite were the solutions that were preserved across multiple generations and only replaced by fitter non-dominated solutions. Zitzler's SPEA inspired other MOEAs to incorporate the elitism strategy, most notably Knowles and Conre's[23] Pareto-Archived Evolution Strategy (PAES) and Kalyanmoy Deb's second attempt at his NSGA algorithm titled NSGA II.[24]

Although many of the MOEAs have advanced dramatically over the last decade (the NSGA III, for example, can now handle problems with 20 objectives while current research aims to increase this number to 100[25]), the comparison between these algorithms is contingent on the algorithms' ability to reach optimality of its solutions yet simultaneously maintain their diversity. This issue becomes highly significant when the variation of the solution set reflects phenotypic diversity within the population, primarily in cases where the formal and geometric attributes of the generated solutions are the required result. Therefore, variation and diversity within a generation – as well as between generations – are essential to users implementing MOEAs for geometric solutions; more importantly however, dynamically controlling variation throughout the simulation run, as well as gaining access to the full historic record of all solutions within the population is essential when the result required is a set of solutions; a set that is selected based on criteria that are independent from the objectives that run the algorithm.

The significance of this relates to the early challenges faced by non-population-based MOEAs of the 1960s, where the user had to apply their weighting preference to the objectives at the end of every generation (by being forced to select one solution to carry on to the next generation); one of the earliest examples of such attempts was in the work by Rosenberg.[26] Although population-based MOEAs have bypassed this condition, they have not foregone it, rather simply delayed it from being applied at every generation to having to be applied at the end of the simulation. However, the question remains, what are the criteria to which the user selects the final – or final set – of solutions? Thus, to limit the user's subjective preference when selecting the solutions, the independent selection criteria mentioned in the paragraph above provides the user with an empirical and informed approach to selecting the final solution set.

Urban application

Elevating the flow of the city

The morphology of cities and the efficiency by which they grow and occupy their environment has gained significant attention.[27] The current urban morphologies developed through lateral growth and centralised nodes of activities have two conflicting objectives: first, to be as compact as possible – centralisation and second, to be as dispersed as possible – decentralisation[28] (Figure 2). In recent years, the dramatic increase (and projected future increase) of urbanised populations has placed an overwhelming demand on the worlds existing cities (both in terms of space and resources). Although the impact of this naturally leads to verticality, this has been implemented within the scale of a single building, yet the city's flow continues to grow laterally at ground level. As a result, the programmes which are parasitic to this system are being distributed at street level, while buildings continue to develop as separate entities vertically. This led to Harvey Wiley Corbett, primarily known for his skyscraper designs, to be one of the first figures to suggest in the early 20th century the integration between multi-level street networks and mixed-used skyscrapers (Figure 3).[29]

Figure 2. Tokyo is renowned for its efforts to decentralise its urban fabric and the many challenges it faced to accomplish this.[30]

Patterns of settlements in many urban areas are transforming from dispersed fabrics to centralised entities with integrated infrastructures.[32] In most cases, their application is in the form of segregated and standalone buildings comprising multiple functions. However, in the cities like Hong Kong, Minneapolis and Calgary, the application of higher level connections has been proven to benefit the urban context. In Hong Kong, traffic congestion, vehicle and noise pollution are the reasons for the incorporation of high-level connections within the urban block (Figure 4). While in Minneapolis and Calgary, their application was in response to the region's harsh climatic conditions, leading to an 18-km network of higher level connections throughout the urban fabric (Figure 5). In addition to their climatic advantages, Corbett et al.[33] argue that such connections allow for greater and more efficient circulation paths across the urban landscape. The term *Skyway* refers to the typology of connections at upper levels between the built environments within the urban block; as such, the emergence of such connections allows the spaces required for these circulatory systems to appear at higher levels across the urban fabric, eventually leading to the formation of multi-level networks of connections across the city.

Vertical distribution of public space

The physical and social structures of a city have a reciprocal influence on one another as they continue to develop.[28] Interactions between individuals happen at different scales and locations within a city. However, these networks of interactions are not constrained to their physical structures, but the variation of such dynamic interactions is surpassing the current physical attributes of cities. Public spaces across the city are examples of such areas, where the spatial structure facilitates the social interactions of its inhabitants. The majority of public spaces accessible to the public are located at the street level, while the network of interactions goes beyond a singular level.

Vertical development resulting from technological advancements and coupled with the shortage of land availability has gained ground in recent years. Cities like Hong Kong and Manhattan are examples of such developments (Figure 6). However, their verticality is applied at the scale of single isolated buildings rather than at the level of the urban fabric, the result of which refrains the distribution of public space to extend beyond the street level. More importantly, these areas have emerged as 'leftover spaces' between the isolated verticality of single blocks. Thus, the experiments presented examine the distribution of public spaces on multiple levels. In addition,

Figure 3. City of the Future by Harvey Corbett was one of the first to propose upper-level connections between skyscrapers of the city.[31]

Figure 4. Pedestrian skyways in Hong Kong emerged from the stresses resulting from the growing population.[34]

rather than emerging as a by-product of the relationship between blocks, the experiments designate a distinct identity to such spaces, allowing for their propagation throughout the urban fabric.

One of the current models for the development of urban forms – *the urban sprawl*, according to Frans Dieleman and Michael Wegner[38] has unintentional consequences, primarily the loss of open space. By

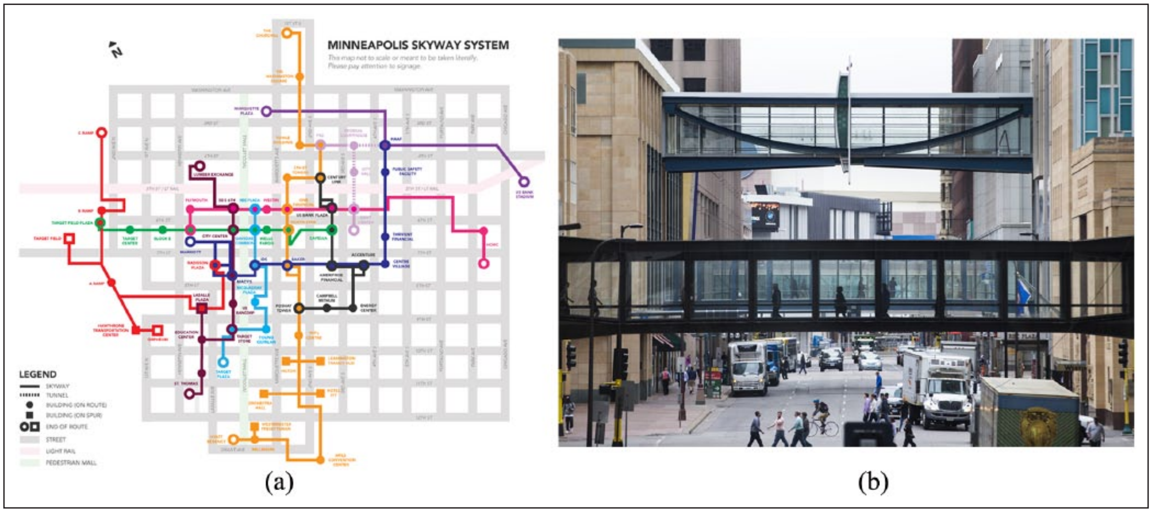


Figure 5. (a and b) Pedestrian skyways in Minneapolis are a response to the extreme climatic conditions of the region.[35,36]

Figure 6. Vertical growth of disconnected buildings has become the norm in many mega cities across the world.[37]

allowing the vertical development and distribution of public spaces, the urban fabric and its organisational structure would transform conventional urban morphologies. Although an urban patch may be constrained to its physical boundaries at ground level, thus limiting the development of public space, the vertical distribution of such spaces bypasses this constraint. Such spaces have great potential to be considered not as isolated rooftops but as a network of spaces connected to one another through skyways. The experiments presented examine the advantageous and disadvantageous of such spaces within the urban landscape.

Neighbourhoods, territories and ecology

The demands imposed by the changing environmental and climatic conditions coupled with a growing demographic has challenged cities' ecological capabilities to adapt to these changes, while the stresses of energy consumption have significantly affected cities' internal environmental and ecological contexts. Although the processes associated with urban variation and development play a pivotal role on the ecological impact on both the local and regional environments, further analysis of these processes necessitates approaching ecological systems as dynamic models, ones that continuously explore and adapt to changing social patterns as well as biophysical properties. As such, an urban ecological model is integral to adaptability, change and flexibility.

In contrast to many of the planned cities of the 20th century, evolving cities have been closely coupled to their immediate territories, with distinct morphologies, integrated infrastructure and urban cultures that have evolved in response to the specific ecological and climatic conditions of the region. As these cities grow and develop in complexity, they have become less dependent on their immediate surroundings by drawing the required energy demands from their local territories.[39]

From this perspective, it has been argued that cities are analogous to living organisms, systems that consume resources and expel their by-products, leading to the notion that urban tissues behave with a high degree of metabolic properties. As such, the term 'urban metabolism' has been prescribed to urban fabrics that transform materials into infrastructure, human biomass and waste, bearing a significant impact on the environmental and climatic conditions that extend beyond the city's limits.[40] In this regard, the goal of urban metabolism is to optimise the metabolic processes of the city by addressing resource generation through an intelligent ecological infrastructure that is integrated within the urban fabric. Therefore, the city's morphology and configuration are crucial in reducing its carbon footprint while simultaneously increasing its adaptability to a changing environment. This is achieved through integrating the ecological infrastructure within the city rather than isolating it to a locale that falls outside the city's territory. More importantly, its integration as part of the urban morphology is critical to increased efficiency of resource extraction and consumption –features that are essential for the urban fabric.

The urban superblock

The block has been utilised as a spatial tool considered to be the most basic element of a city's development. Its evolution is traced back to early migratory groups that occupied pit houses (or in some cases courtyard houses) that were well adapted to the environmental and climatic conditions as well as the population's cultural values. Their distribution (and relationship thereof) developed into becoming the dominant organisational urban element that formed urban settlements. However, as urban tissues continue to grow, the basic element of the block has become nested into forming what is referred to as a superblock; a collection of blocks that are related to one another through their formal distribution and morphological properties. As the scale and the capacity of the urban tissue continues to expand, these superblocks become interrelated at a regional level evolving into urban patches of varying sizes.

There are countless examples of nested blocks that vary in size, morphology and occupancy; in the case of the ancient Greek city of Miletus, blocks – primarily in the form of courtyard houses – were approximately 30 m × 30 m in footprint, while in 15th century Beijing, courtyard blocks were nested in a 150-m grid throughout. In modern day Barcelona, the block with inner courtyard has grew in size to occupy a footprint of 100 m × 100 m, arrayed throughout the city in the form of superblocks that have become core to Barcelona's urban landscape.

In contrast to historical precedents, modern day examples of superblocks are predominantly uniform in size, distributed in equal uniformity across the urban landscape. However, many evolving cities exhibit blocks and superblocks that vary substantially in both their morphology and distribution. Through sampling different urban patches (both evolving and planned), one can extract a block's (or superblock's) specific formal features and typologies. Case in point, the city of Fes in Morocco, a city evolved through its blocks' strong adaptability to its environmental, climatic and geographic context, while encoding within the formal distribution of the city's block's a spatial representation and value of its people's culture.

David Grahame Shane[41] describes the superblock as an enclave that is bounded by space and defined by a perimeter with clear access points and distinct centre. As an urban organisational tool, it carries with it several urban functions and processes that serve as the basis for adaptability to environmental and climatic change. Thus, its functionality, morphology and infrastructural qualities are crucial to its impact on its surrounding ecology. As such, the experiments presented within this paper utilise the block as the basic urban component from which the urban patch is evolved. In specific, the property of a block located in the city of Fes is the primitive morphological element that has been selected to which a superblock is derived from and transformations are applied to.

The Medina of Fes

The Medina of Fes (or Fes el Bali), located in the north-eastern region of Morocco, has been listed as a world heritage site by UNESCO in 1981 for the perseverance and influence of its history, culture, architecture, urban landscape and heritage throughout the past millennia to modern day.[42] The *medina* is characterised through a unique urban landscape, a highly compact and dense distribution of two to four storey blocks and superblocks that synthesise the city's Islamic culture and heritage through inward looking courtyards. It is this association between the Islamic culture's value of privacy and the morphological distribution of blocks within the city that defines one of the most intriguing traits of the medina, the differentiation yet seamless relationship between private, semi-private and public spaces distributed throughout the urban tissue.

The irregular distribution of blocks and superblocks within the city has resulted in the medina being appropriated with a highly pedestrianised urban landscape. Vehicular traffic is limited to a small number of streets, while the majority is allocated to foot traffic. The hierarchical differentiation between public and private continues to manifest itself through the medina's street network, where streets vary significantly in width which in turn reflects the requirement for privacy (or openness) within the public spaces. More importantly, the irregular distribution of blocks coupled with the varying street network holds a significant impact on the solar gain on street level, with many of the streets lying in shade due to the irregular morphological distribution throughout the urban tissue.[43]

As with many cities throughout the world, the city of Fes is experiencing increasing rates of population growth within a very short time frame. The city's population has almost tripled in size since the medina has been listed as a world heritage site in 1981, with the impact of the increasing population affecting the medina's urban fabric and sprawl.[44] As well as generating considerable stresses on the environment and resources of the medina, the city's stakeholders have been impacted by the struggle for a continuously decreasing supply of land, with a direct competition between residents, small business owners and large businesses, each fighting for their space within the city. The following experiment attempts to reconfigure the morphological and urban distribution of the medina to address issues of climate, ecology and city context while simultaneously maintaining the original morphological characteristics of the city's superblocks which have persisted across millennia.

The experiment

The morphological variation of urban form and its response to different environmental and climatic conditions is approached through the application of a biological evolutionary model that utilises the superblock (detailed above) as the primitive geometry (or individual) to which transformations (or genes) will be applied to and consequently analysed for selection. The intent is to utilise an evolutionary process of variation (through crossovers and mutations), evaluation (analysis of the generated individuals according to how well they perform to the fitness conditions) and selection (ranking the individuals and selecting the ones to survive and persist in future generations and the ones that will be deemed too unfit to survive) that generates a population of individuals across multiple generations which differ in morphology and distribution, yet simultaneously maintain high levels of fitness throughout.

The urban conditions described above of vertical connectivity between urban blocks, elevated public spaces, neighbourhoods, territories, ecological context and the control of solar gain on ground level to increase solar comfort are incorporated as fitness objectives to which the primitive (the Fes superblock) will aim to optimise for. Throughout the evolutionary simulation, the different urban forms will be evaluated (both statistically and morphologically) in an attempt to highlight emergent behaviour among the evolved solutions at either the level of a single superblock or between superblocks across multiple generations. The experiments will present these behavioural traits through the analysis of individual solutions extracted from different generations throughout the simulation as well as a comparative statistical analysis of every 100th generation.

Experiment setup

As the design experiments presented in this paper aim to generate a population of superblocks that have ‘evolved’ towards multiple conflicting objectives, the Strength Pareto Evolutionary Algorithm 2 (SPEA-2) has been selected to run the experiment (Figure 7). The SPEA-2 is the driving algorithm behind the software *Octopus*, a free plugin written for *Grasshopper 3D* by Robert Vierlinger. It is prudent that the simulation is run on a consumer-specification computational platform; this ensures the computational load is kept within a reasonable range and thus does not necessitate the use of a commercial ‘super computer’. As such, the computational platform running the simulation is a 2.8-GHz Intel Core i7 laptop with 16 GB allocated for memory.

Utilising the urban block of the city of Fes in Morocco as the basic geometric component (Figure 8), a primitive was constructed comprised from a 5 × 5 superblock (Figure 9).

The objective of the experiment is to generate a population of superblocks that attempt to optimise for the following fitness criteria: (a) an increase in the area of neighbouring open spaces around each block cluster (Figure 10(a) and (b)), (b) an increase in the area of elevated public open spaces and walkways (Figure 10(c) and (d)), (c) an increase in the distance between upper and lower level open spaces (Figure 10(e) and (f)) and (d) a decrease in solar exposure on street level (Figure 10(g) and (h)). Each of these objectives is directly correlated to morphological transformations used to construct the form of each superblock; in the context of the evolutionary engine, these transformations are considered as the ‘genetic code’ (or genome) of the superblock. The superblock’s genome comprises the following transformations (‘genes’).

Buildings in the urban patch cluster around each other based on their proximity and form neighbourhoods in the phenotype. These neighbourhoods may overlap or even share common ground. What is left after subtracting the footprint of the built areas from the neighbourhood boundary are the superblock’s open spaces. *The adjacent open spaces* within a neighbourhood in the context of this article refer to designated spaces available to each neighbourhood within its territory. The design experiment aims to increase social interactions within the urban fabric by increasing the area of such spaces in an attempt to generate diverse spatial qualities within each phenotype (Figure 11).

The significance of networks and public spaces on upper levels throughout the urban fabric has been discussed in previous sections; thus, the superblock is constructed to allow the phenotype to develop these spaces and connections should the algorithm favours such solutions, allowing for greater numbers of public spaces that are not bound to the street level. As the rate of upper-level spaces increases, the simulation is driven towards increasing the connectivity among them by initiating upper-level walkways throughout the superblock (Figure 12). This also ensures circulation and movement are not constrained to the street level.

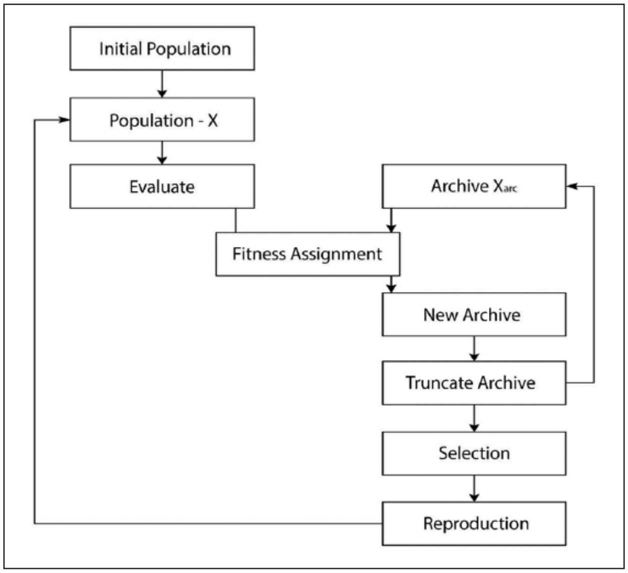


Figure 7. The algorithmic workflow of the Strength Pareto Evolutionary Algorithm 2 (SPEA-2) by Eckart Zitzler.

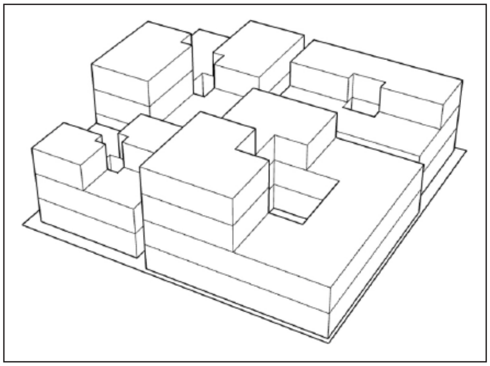


Figure 8. The city of Fes urban block, the basic element used in the primitive for the experiments.

By increasing the distance between open spaces, their accessibility from various parts of the superblock is optimised, allowing for greater connectivity to these spaces while simultaneously encouraging verticality rather than horizontality (Figure 13). Finally, decreasing the solar exposure on the ground level ensures high degrees of overshadowing and allows for greater distribution and clustering of the blocks within the superblock (Figure 14).

To accomplish this, various transformations control the phenotype's morphology through modifications that comprise moving the initial boundaries of the primitive in the XY plane, as well as changes in courtyard sizes, building heights and dimensions (Figure 15). In addition, the transformations also allowed for the emergence of connections between selected blocks and their respective elevated open spaces. The relationship between the blocks and the open spaces is driven by a fall off area attributed to each elevated open space (Figure 10(b)).

Although the application of a MOEA incorporates selection and variation strategies to eventually drive the population towards an optimal solution set, the intensity of their application is essential to maintain

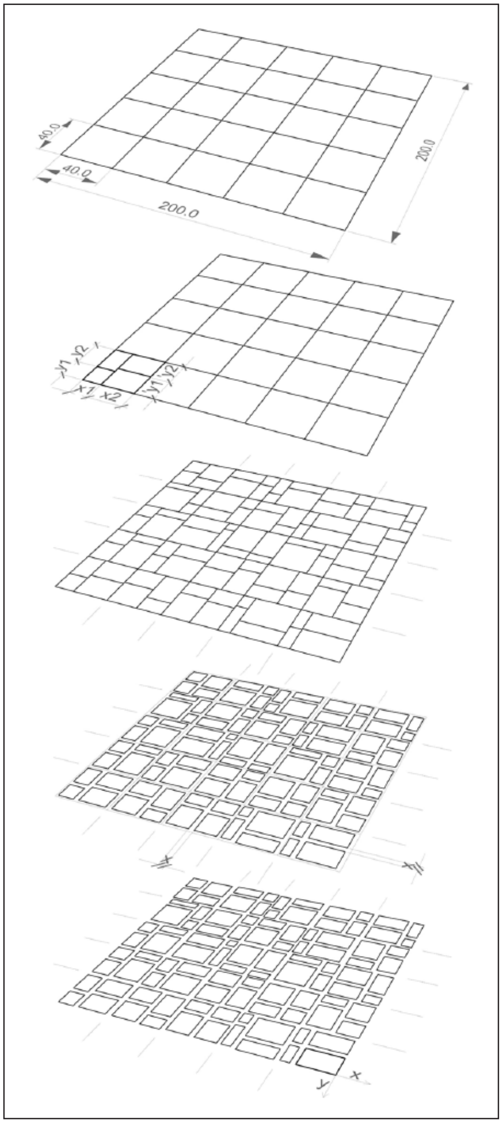
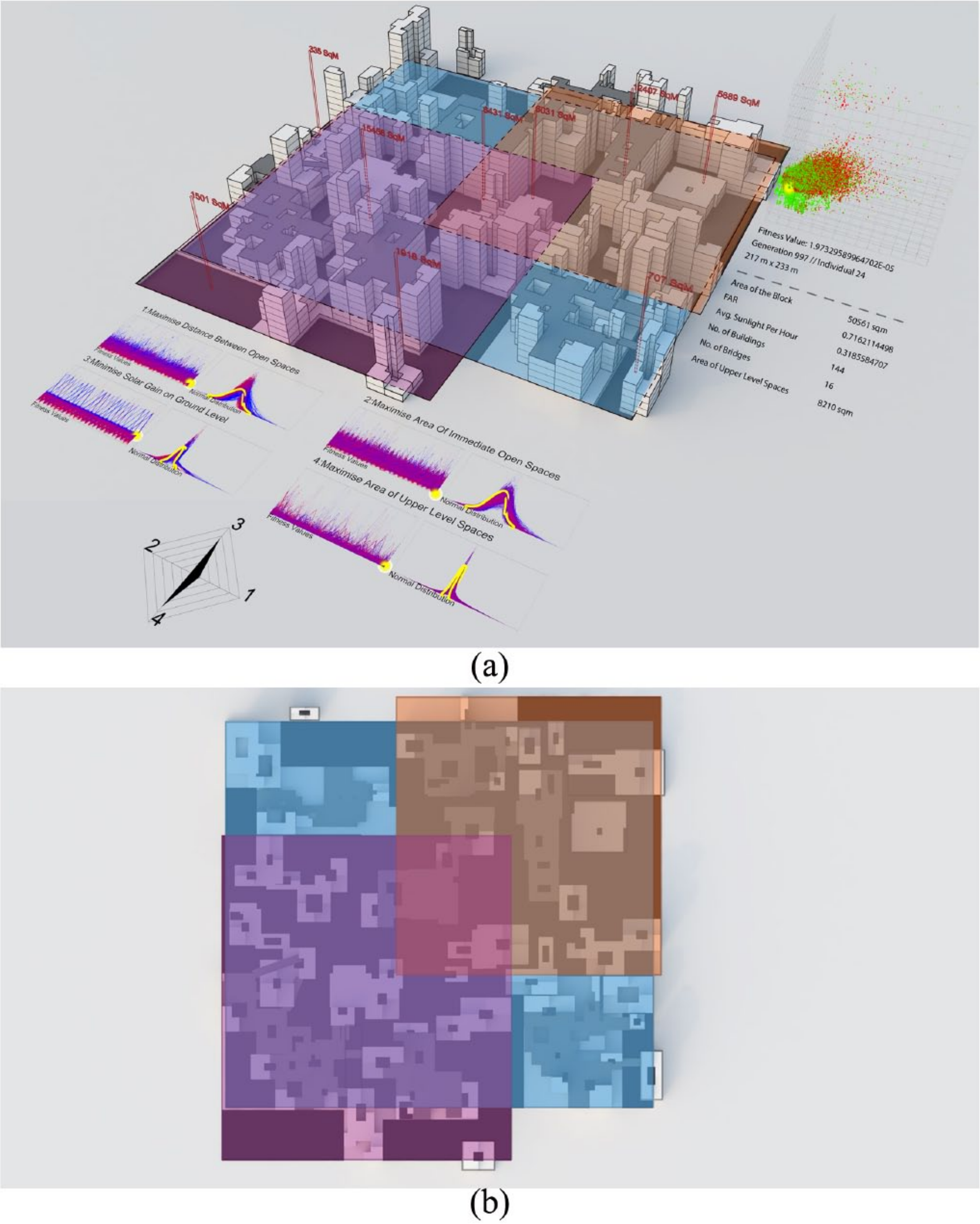


Figure 9. The Fes urban block was nested into a 5 × 5 superblock. This superblock was the primitive for the algorithm. In the article, this is referred to as the ‘individual’ or the ‘solution’.

variation across the population without loss in fitness. Ideally, the algorithm should establish a search and optimisation strategy that is both explorative – adequate mutation and crossover rates to allow for a diverse population of candidate solutions – and exploitative – utilising elitism strategies to converge the population towards an optimal solution set.[45] As such, the algorithm parameters were set to the following: mutation rate – 50%, mutation probability – 20%, crossover rate – 80% and elite size at 50%. Finally, taking into account the complexity of the problem at hand, the simulation was limited to 25 individuals per generation with a total simulation runtime of 1000 generations (for a more detailed description and definitions of the algorithm parameters, please see Makki et al.[46]).


335 SqM
15458 SqM
3431 SqM
8031 SqM
12407 SqM
5689 SqM
1501 SqM
1918 SqM
707 SqM
Fitness Value: 1.97329589964702E-05
Generation 997 // Individual 24
217 m x 233 m
Area of the Block
FAR
Avg. Sunlight Per Hour
No. of Buildings
No. of Bridges
Area of Upper Level Spaces
50561 sqm
0.7162114498
0.3185584707
144
16
8210 sqm
1.Maximise Distance Between Open Spaces
Fitness Values
Normal Distribution
2.Maximise Area Of Immediate Open Spaces
Fitness Values
Normal Distribution
3.Minimise Solar Gain on Ground Level
Fitness Values
Normal Distribution
4.Maximise Area of Upper Level Spaces
Fitness Values
Normal Distribution
1
2
3
4
(a)
(b)

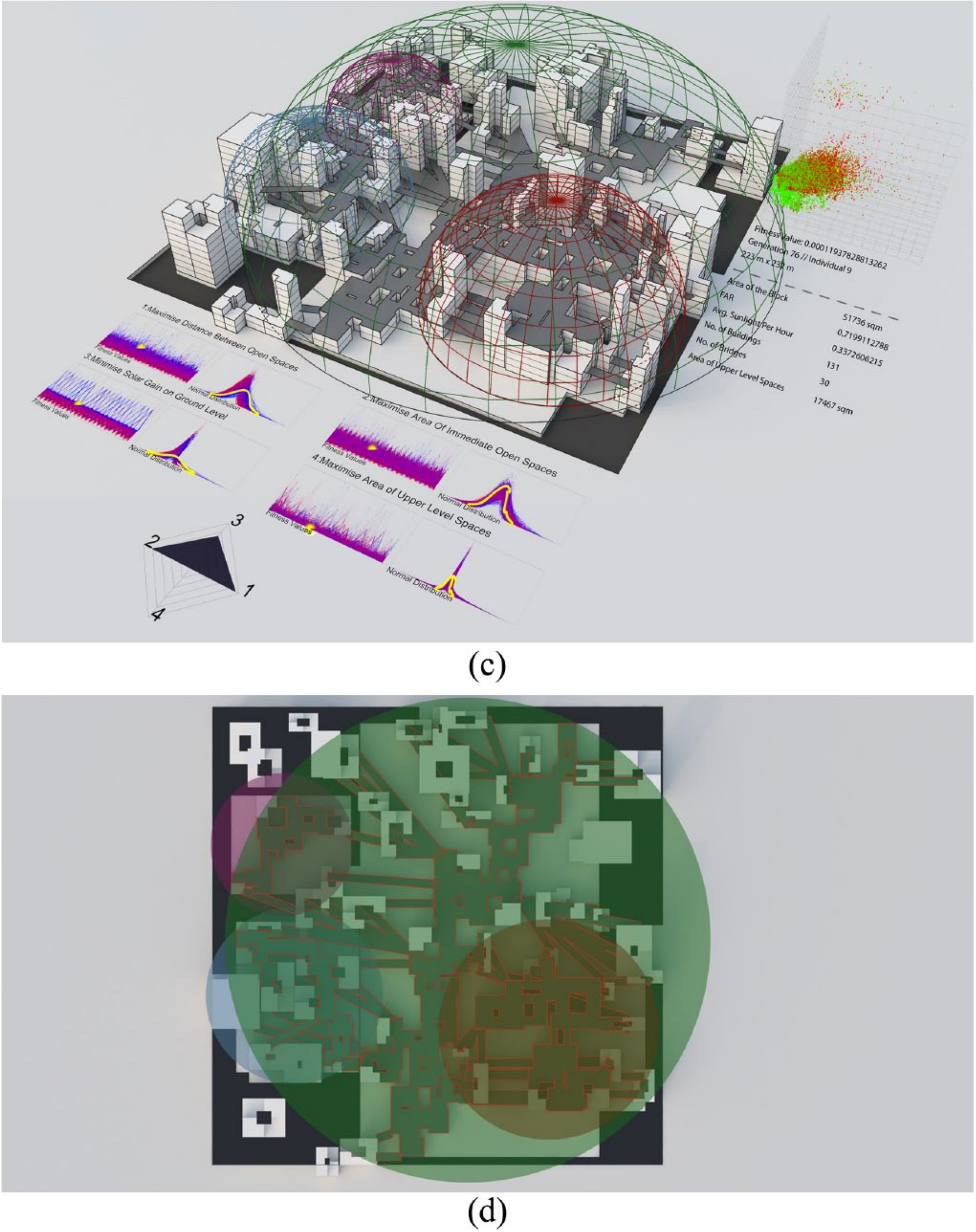
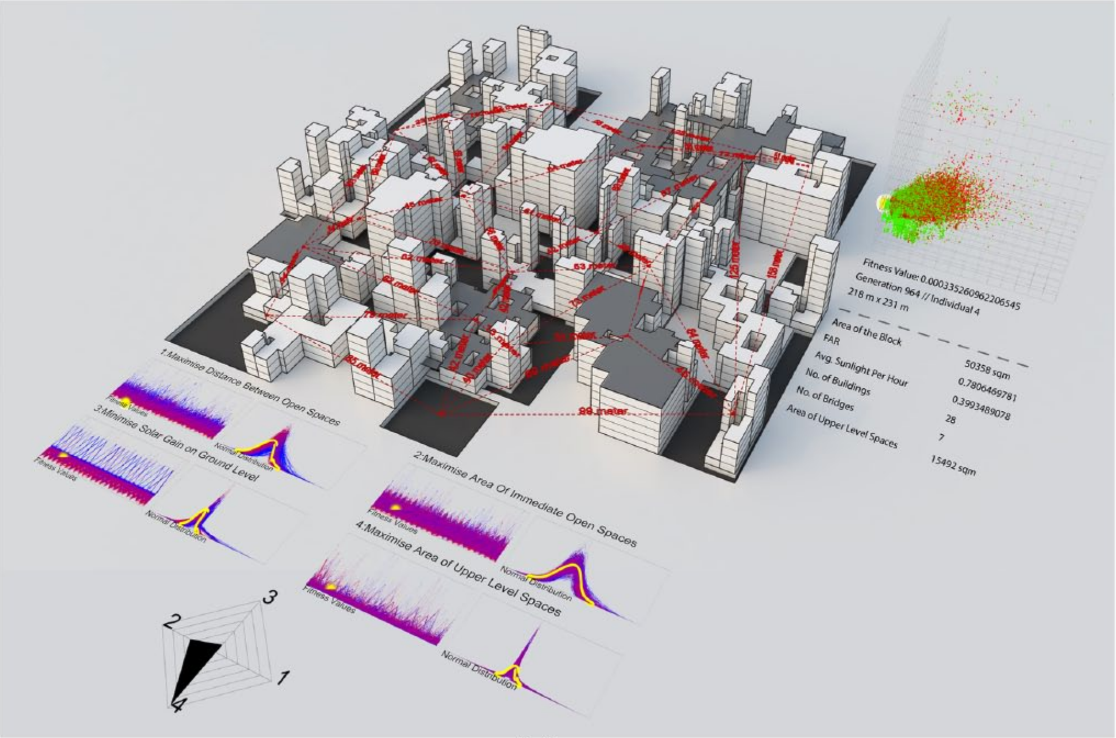
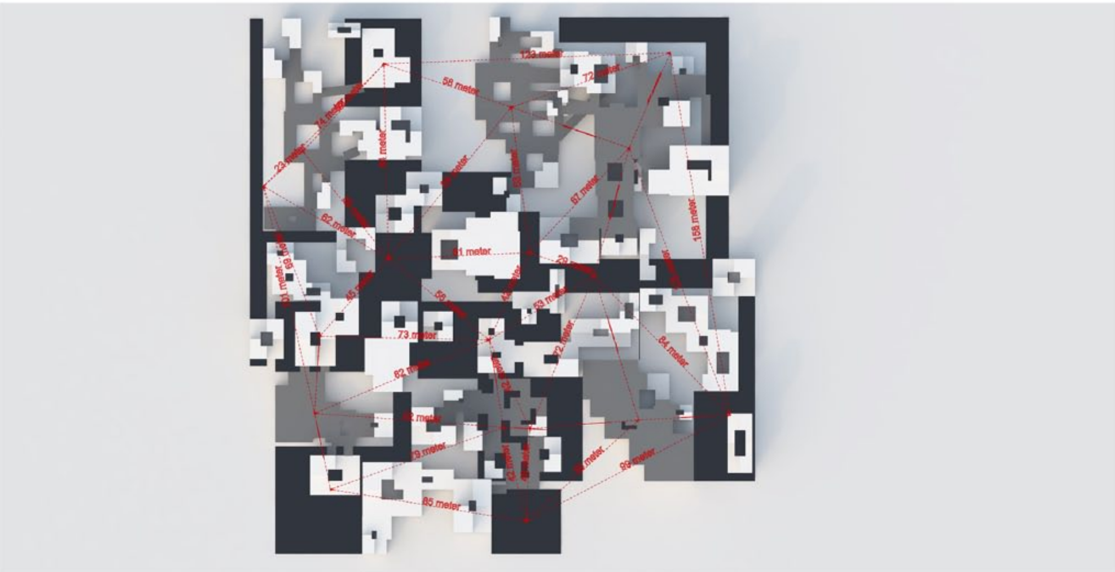


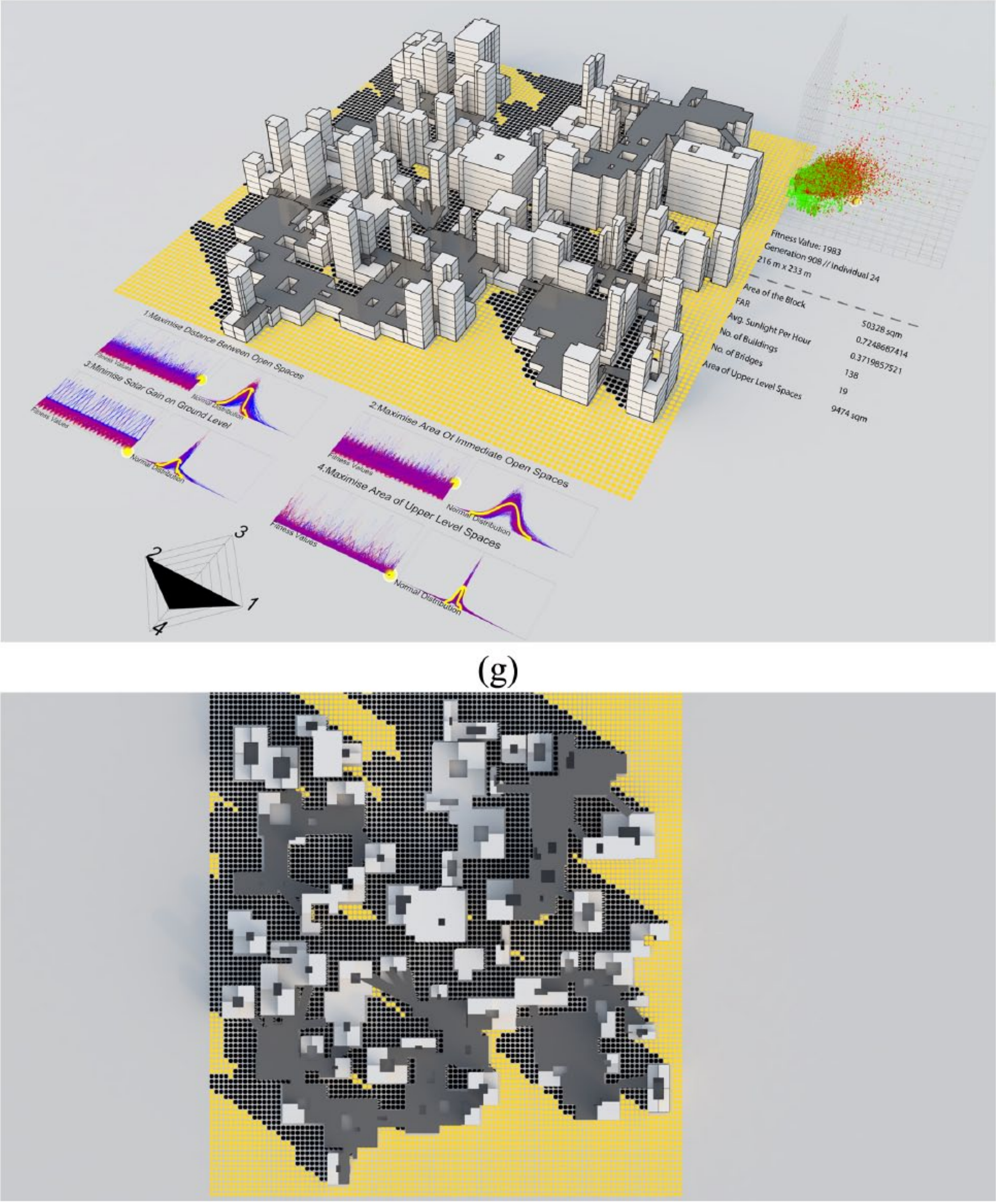
Figure 10. *(Continued)*


Fitness Value: 0.000335260962206545
Generation 964 // Individual 4
218 m x 231 m
Area of the Block
FAR
Avg. Sunlight Per Hour
No. of Buildings
No. of Bridges
Area of Upper Level Spaces
50358 sqm
0.7806469781
0.3993489078
28
7
15492 sqm
1.Maximise Distance Between Open Spaces
Fitness Values
Normal Distribution
3.Minimise Solar Gain on Ground Level
Fitness Values
Normal Distribution
2.Maximise Area Of Immediate Open Spaces
Fitness Values
Normal Distribution
4.Maximise Area of Upper Level Spaces
Fitness Values
Normal Distribution
3
2
1
4
99 meter
75 meter
85 meter
158 meter

(e)


123 meter
58 meter
72 meter
74 meter
23 meter
62 meter
81 meter
67 meter
158 meter
73 meter
82 meter
79 meter
85 meter
84 meter
99 meter

(f)



(g)

(h)

Figure 10. *(Continued)*

Figure 10. (a) Perspective of the allocation and distribution of the adjacent open spaces within the superblock. (b) Plan of the allocation and distribution of the adjacent open spaces within the superblock. (c) Perspective of the connection logic of upper level skyways. (d) Plan of the connection logic of upper level skyways. (e) Perspective of the calculation of maximising distances between open spaces. (f) Plan of the calculation of maximising distances between open spaces. (g) Perspective visualisation of the solar distribution on ground level. A finite number of vertices were distributed on ground level for the solar calculation. (h) Plan visualisation of the solar distribution on ground level. A finite number of vertices were distributed on ground level for the solar calculation.

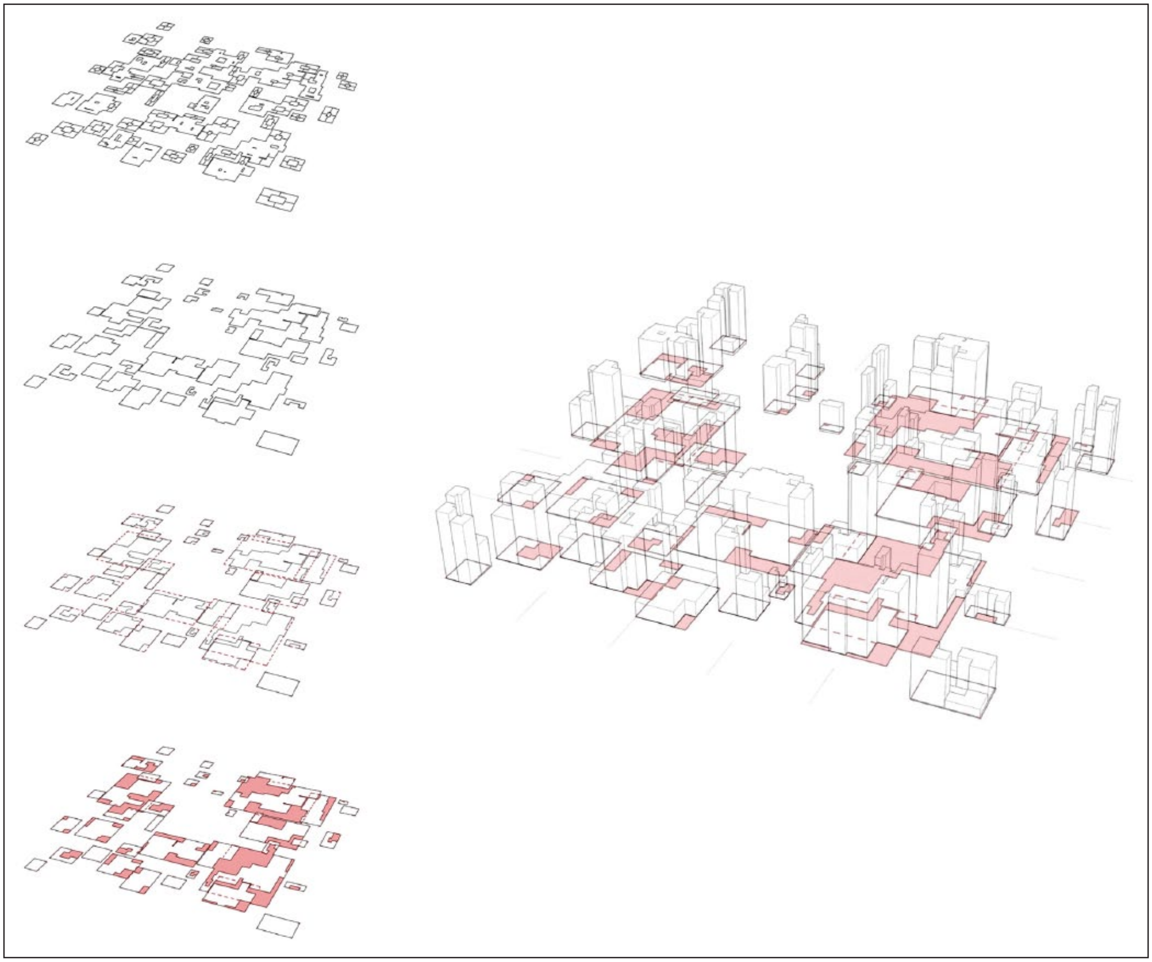


Figure 11. Development and calculation of the adjacent open spaces objective.

Results

The result of the algorithm's run produced 25,000 genotypes/phenotypes with four fitness values per solution, totalling to 100,000 values. To visually analyse the morphologies of each solution is highly inefficient, more importantly, subjective to the visual evaluation set by the user. Therefore, statistical analysis of the generated solutions plays a significant role in the selection and modification of the optimal solutions. Unlike SOEAs, MOEAs do not converge to a single solution at the end of the simulation (unless the fitness

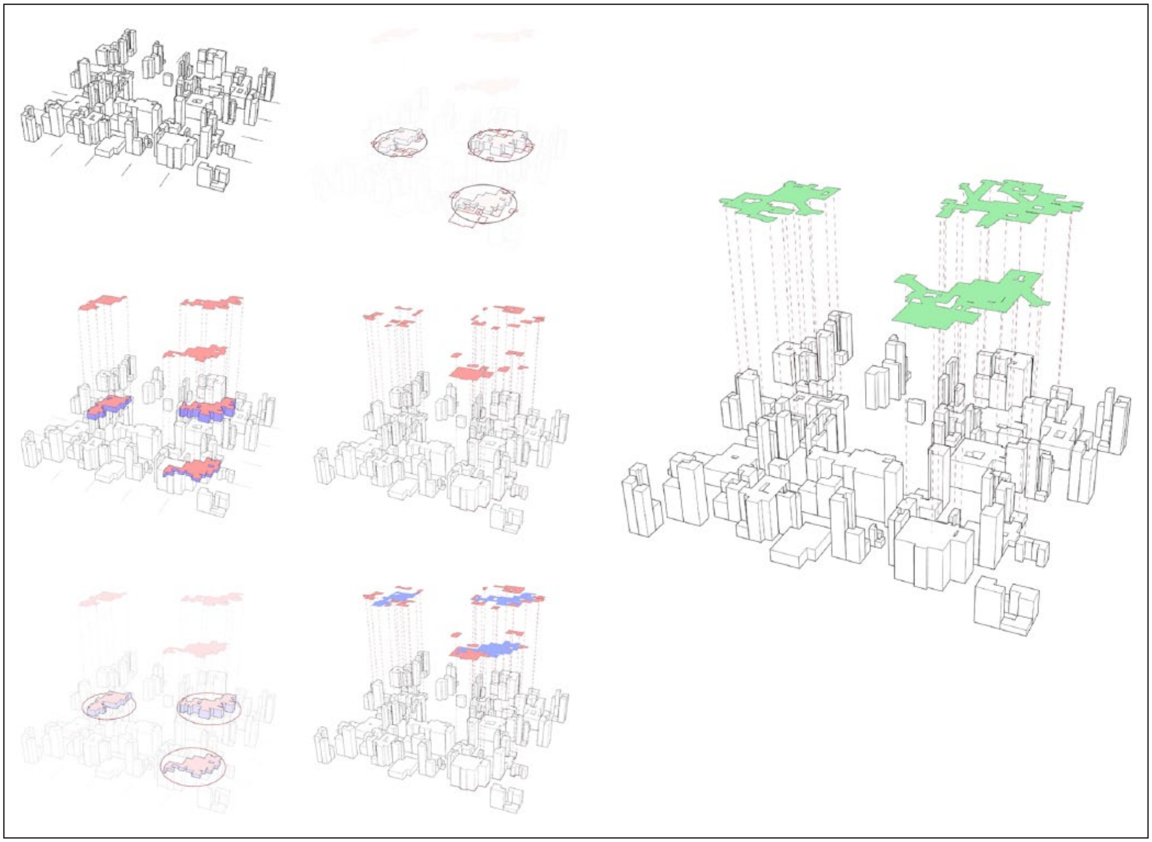


Figure 12. Development and calculation of the elevated open spaces objective.

objectives were not in conflict); thus, the method of selecting a desirable solution set was explored through the analysis of individual solutions as well as across each generation.

The first analysis performed was to ensure for a unified understanding across the entirety of the simulation run; therefore, every 100th generation was selected for visualisation and evaluation in an attempt to observe the diversity of solutions within generations as well as their evolution across the simulation. The variation and convergence of solutions in each of the selected generations are evaluated by means of their Normal Distribution (as well as the comparison of the generation's normal distribution across the entire simulation) and the distribution of the Pareto front solutions (the solutions that are not Pareto dominated by any other solution). With regard to the normal distribution, the standard deviation factor for each criterion is calculated, with the presented generation's normal distribution curve highlighted (Figure 16). For the first criteria (increasing distance between public spaces), the simulation evolved solutions with greater fitness yet maintained an adequate level of variation across the population. For the second criteria however (increasing the areas of neighbouring open spaces), the algorithm maintained variation yet could not evolve towards any considerable increase in fitness. As for the third criteria (decrease solar exposure on street level), the simulation increased the fitness of solutions; however, there were a few instances of high convergence among population. Finally, fourth criteria (increase area of upper level open spaces) had the greatest fluctuation among the four criteria, with a constant back and forth between variation and convergence throughout the entirety of the simulation run.

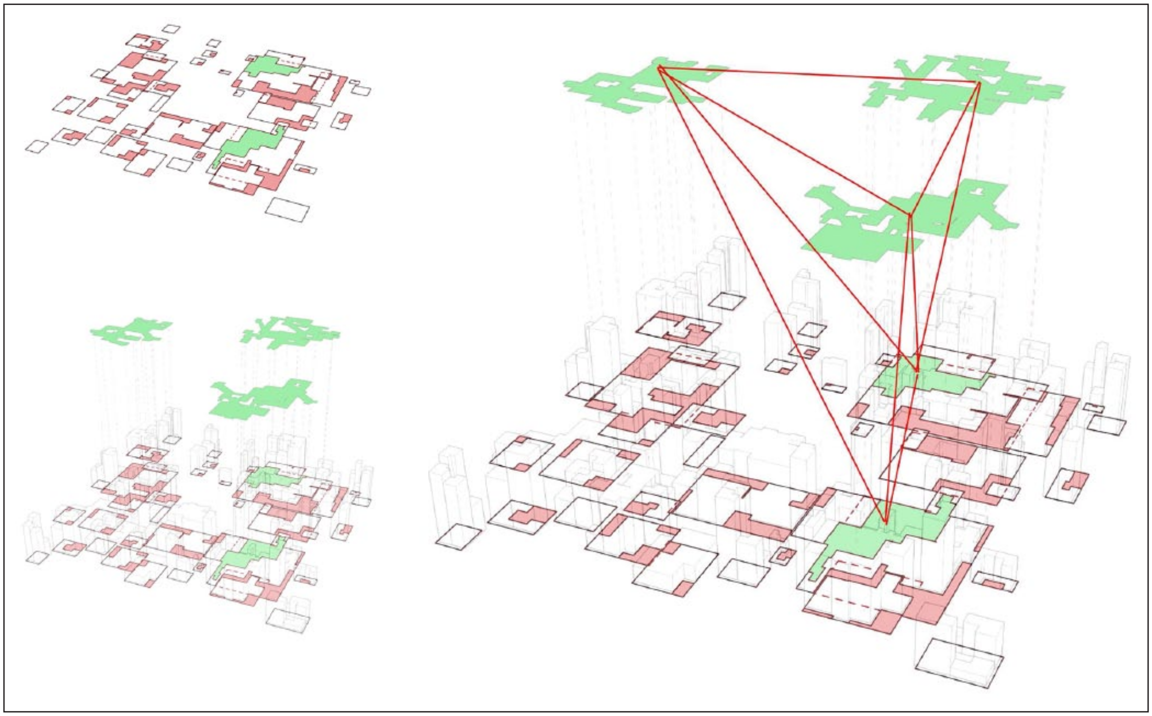


Figure 13. Calculation of the maximising distances between open spaces objective.

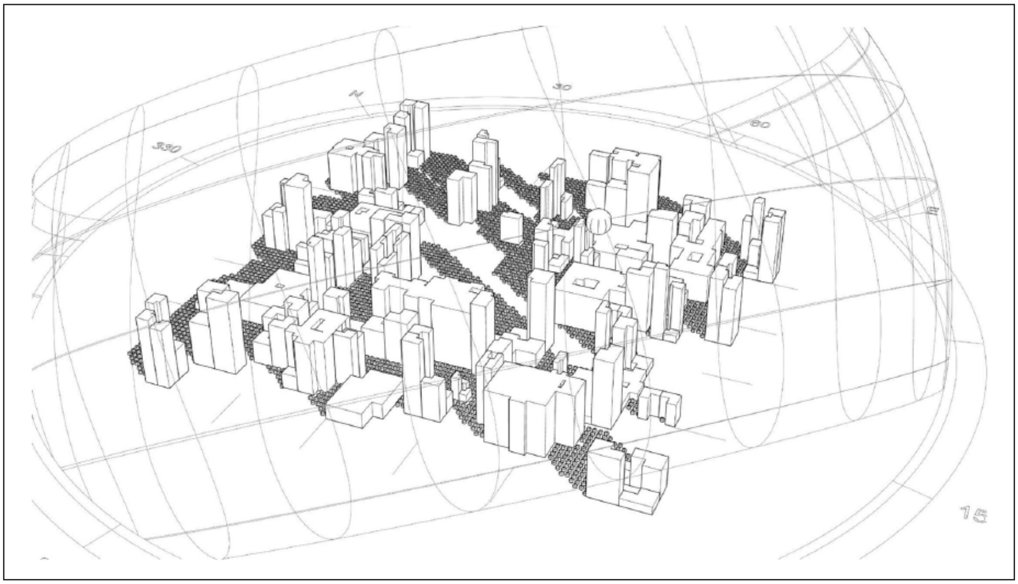


Figure 14. Calculation of the solar exposure with regard to a single vector. Only one vector was used due to computational limitations of the calculation.

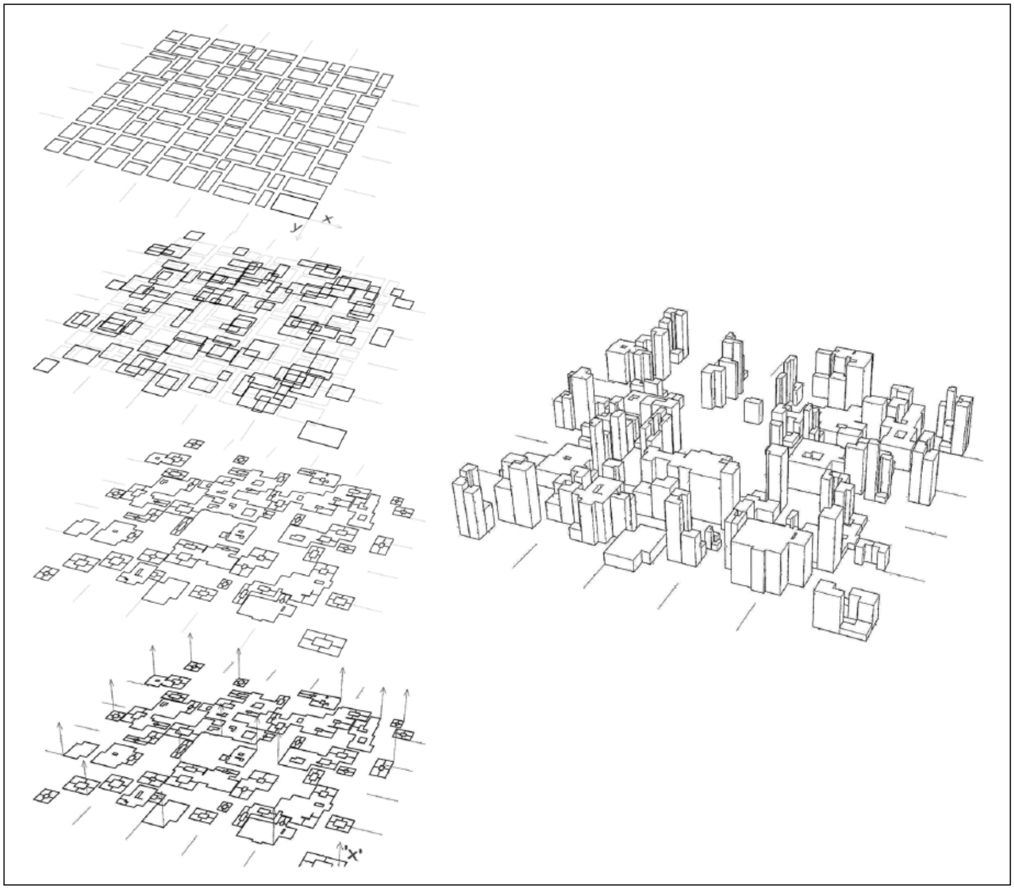


Figure 15. The algorithm was given the opportunity to transform the blocks within the superblock in their x,y plane, as well as by modifying their footprint, distribution, courtyard size and height.

With regard to the Pareto optimal front, the distribution of solutions was somewhat uniform throughout the simulation, emphasising the conflict between the criteria and the inability for any one criterion to drive the simulation more than the others (Figure 17). It must be noted, however, that although each generation produced 25 phenotypes, a small selection of these phenotypes were considered to be ‘errors’; this was a result of the algorithm’s failure to compute some of the phenotypes, thus unable to provide fitness values for these ‘error’ solutions (Figure 18). As such, these solutions were culled from the analyses and are not presented within this article’s results.

In addition to the analysis of solutions at the generation level, 10 solutions were selected among the 25,000 individuals to examine how efficient the simulation optimised their objectives. As discussed in earlier sections, selecting a single solution (or group of solutions) for an MOEA with conflicting criteria while attempting to limit the user’s preference is a challenging topic. The following strategy attempts to bypass this issue; however, the authors believe that this presented strategy continues to be highly dependent on the fitness objectives running the simulation; current research conducted by the authors is investigating an alternative method for selection through the application of external fitness criteria independent from the simulation. The strategy is as follows; each of the 25,000 solutions was ranked according to each fitness criterion from

Figure 16. Analysis of every 100th generation of the simulation run. The normal distribution graphs present the distribution of all generations within the population, going from blue (earliest generation) to red (attest generation). The generation presented is highlighted in yellow. The accompanying Pareto distribution graph presents the distribution of individuals of the respective generation across the Pareto front.

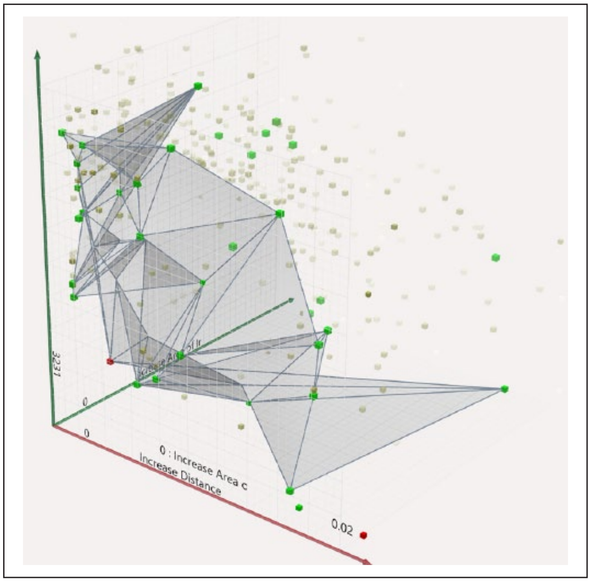


Figure 17. The Pareto front distribution of solutions within a generation. The distribution of phenotypes clearly delineates conflict between the optimising criteria.

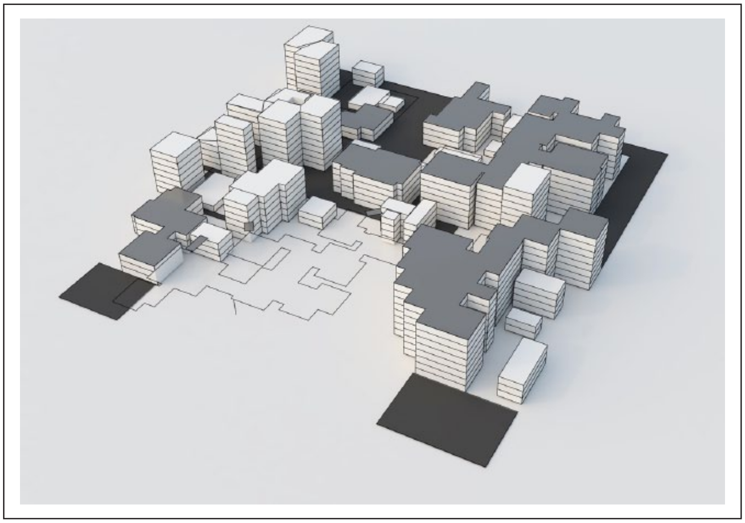
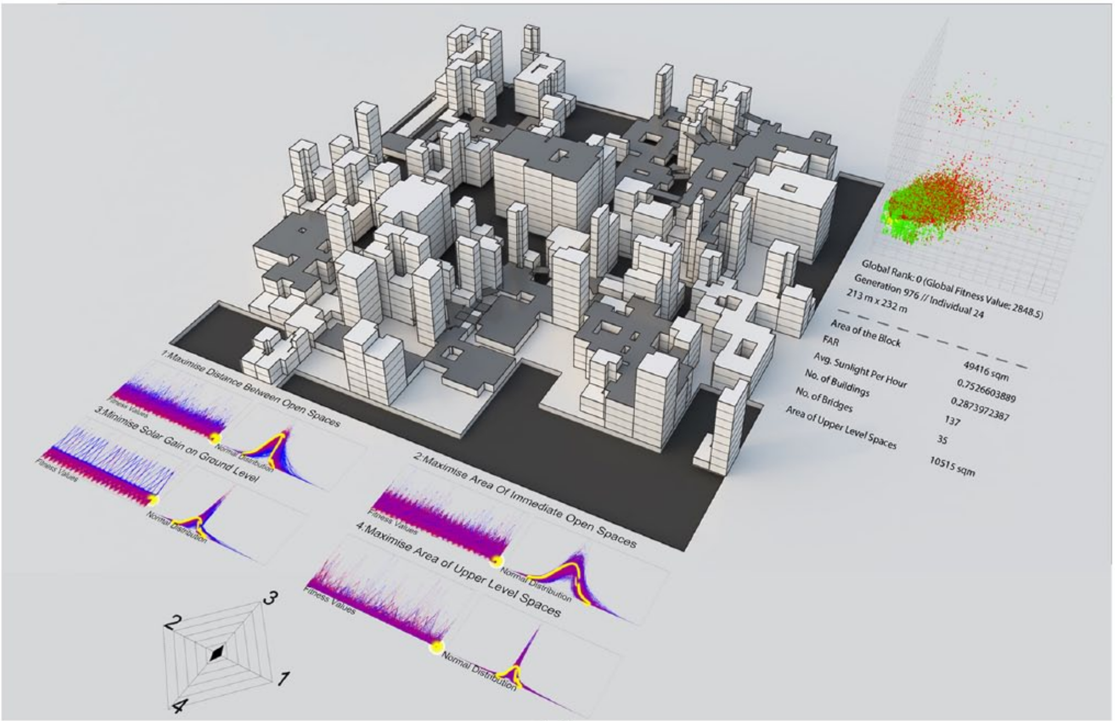
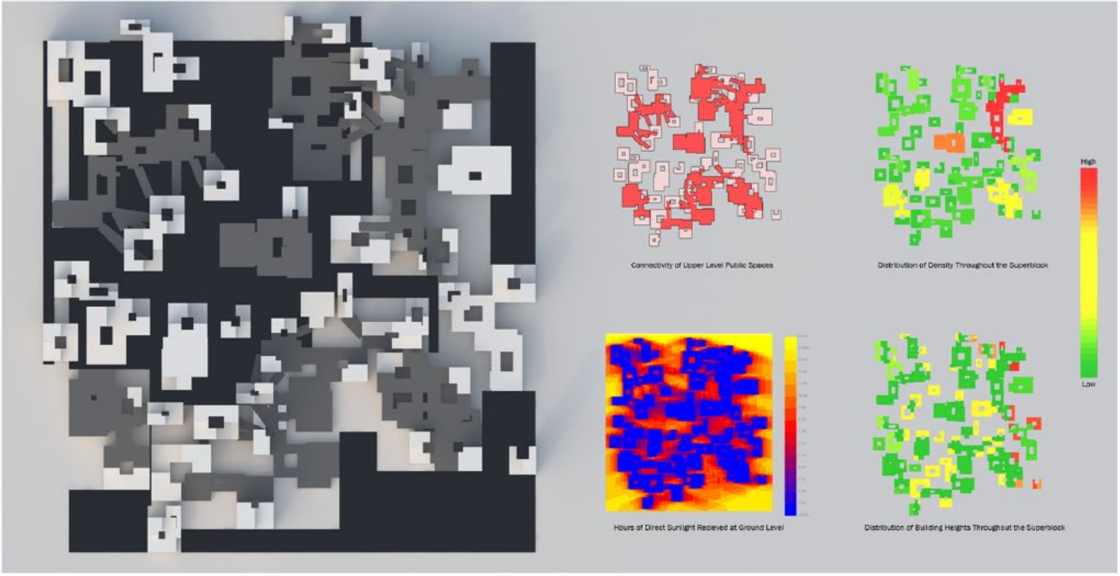


Figure 18. An example of the anomaly; in such cases, the algorithm could not compute the inner courtyard areas which resulted in unexpected geometry throughout the superblock.

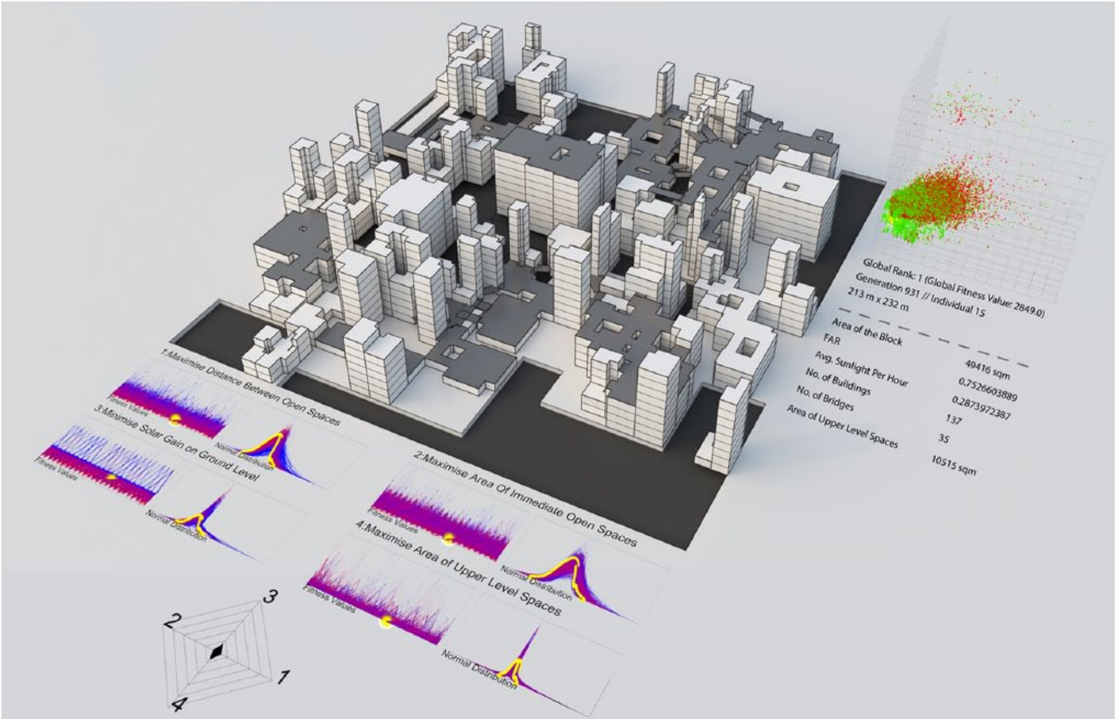
fittest to least fit assigning each solution a unique integer starting at 0; this is a population wide ranking and not a generation based one. When all individuals have been assigned their rank, each solution will hold four unique numbers, a number to represent each criterion. It is the accumulation of these four numbers which then represents what is referred to as the global ranking of each solution. According to this method, the individuals with the top 5 global ranks are chosen to be visualised, investigated and analysed.


Global Rank: 0 (Global Fitness Value: 2848.5)
Generation 976 // Individual 24
213 m x 232 m
Area of the Block
FAR
Avg. Sunlight Per Hour
No. of Buildings
No. of Bridges
Area of Upper Level Spaces
49416 sqm
0.7526603889
0.2873972387
137
35
10515 sqm
1:Maximise Distance Between Open Spaces
3:Minimise Solar Gain on Ground Level
2:Maximise Area Of Immediate Open Spaces
4:Maximise Area of Upper Level Spaces
Fitness Values
Normal Distribution
1
2
3
4

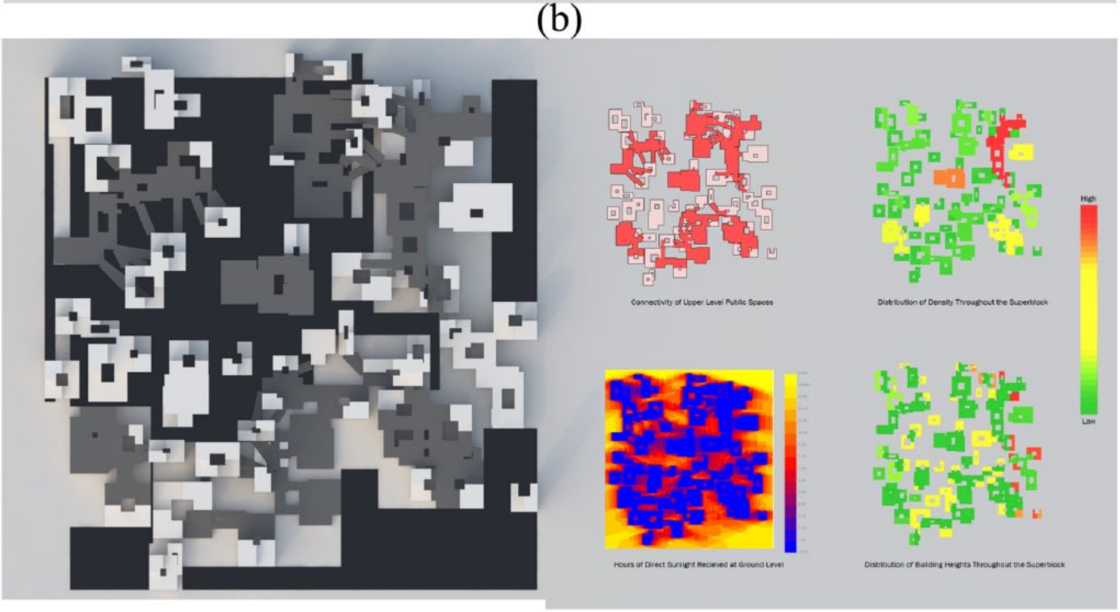
(a)


Connectivity of Upper Level Public Spaces
Distribution of Density Throughout the Superblock
Hours of Direct Sunlight Recieved at Ground Level
Distribution of Building Heights Throughout the Superblock
High
Low

(a_plan)

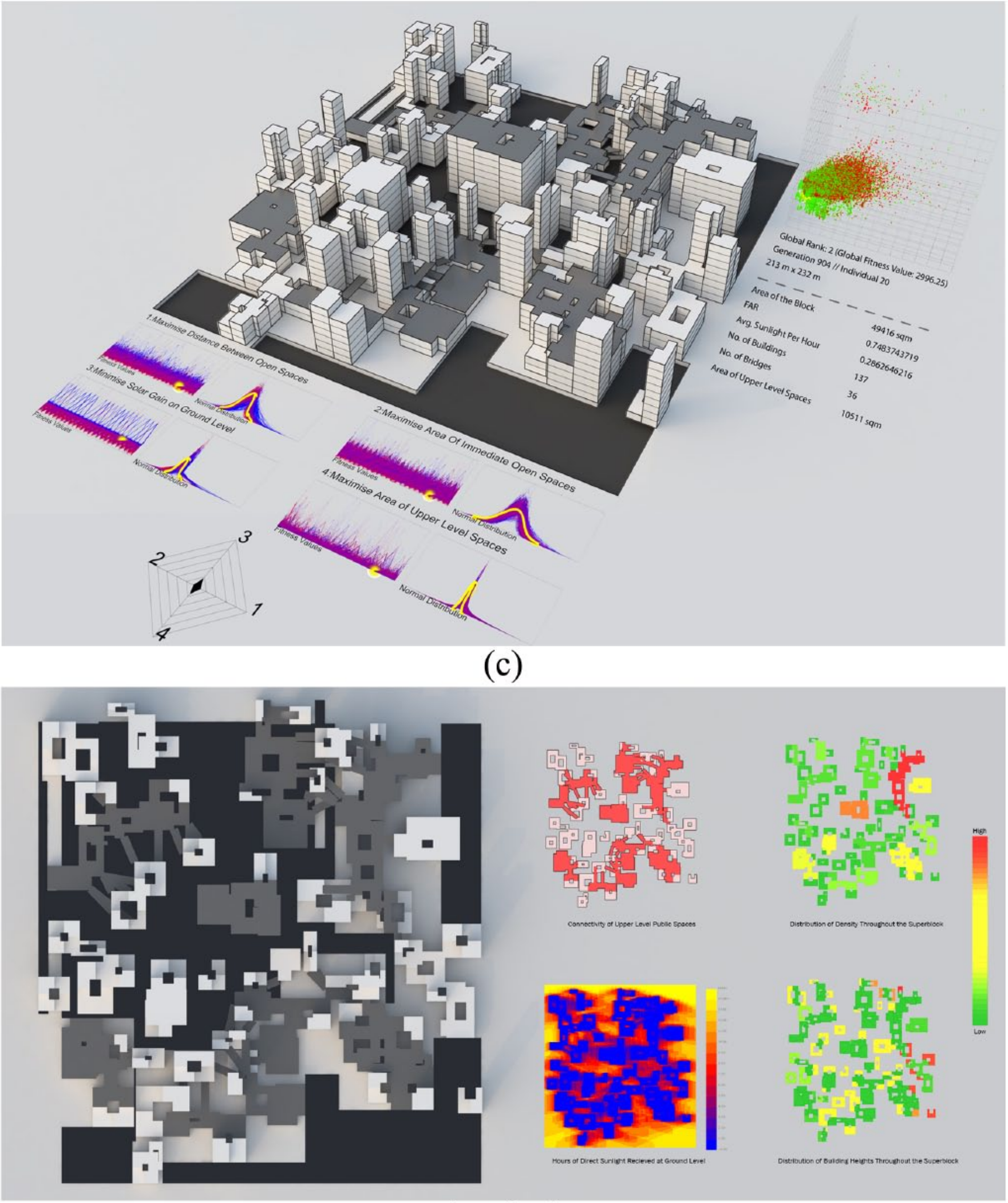


(b)



(b_plan)

Figure 19. *(Continued)*


Global Rank: 2 (Global Fitness Value: 2996.25)
Generation 904 // Individual 20
213 m x 232 m
Area of the Block
FAR
Avg. Sunlight Per Hour
No. of Buildings
No. of Bridges
Area of Upper Level Spaces
49416 sqm
0.7483743719
0.2862646216
137
36
10511 sqm
1:Maximise Distance Between Open Spaces
2:Maximise Area Of Immediate Open Spaces
3:Minimise Solar Gain on Ground Level
4:Maximise Area of Upper Level Spaces
Fitness Values
Normal Distribution
1
2
3
4
Connectivity of Upper Level Public Spaces
Distribution of Density Throughout the Superblock
Hours of Direct Sunlight Recieved at Ground Level
Distribution of Building Heights Throughout the Superblock
High
Low

(c)

(c_plan)

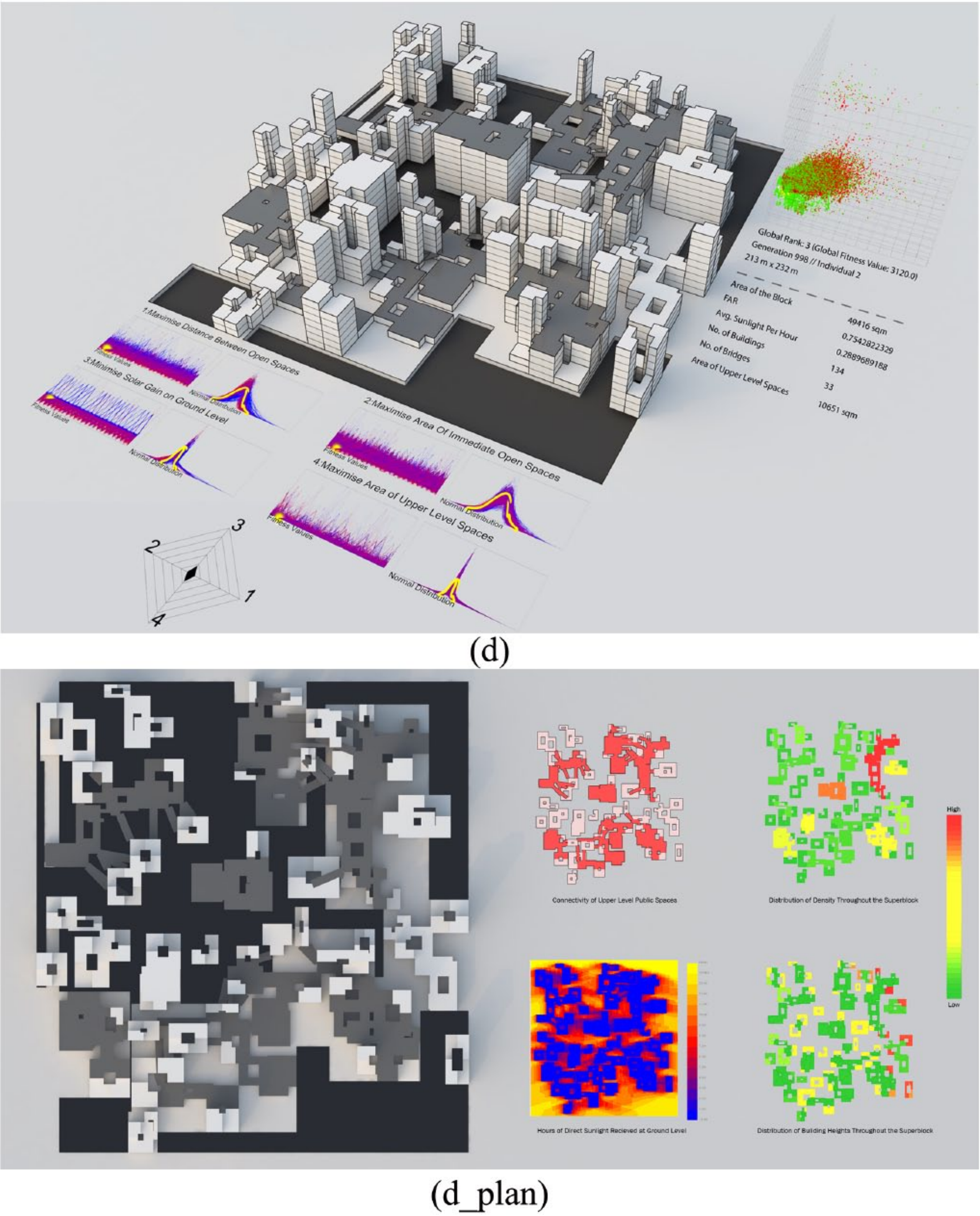


Figure 19. *(Continued)*

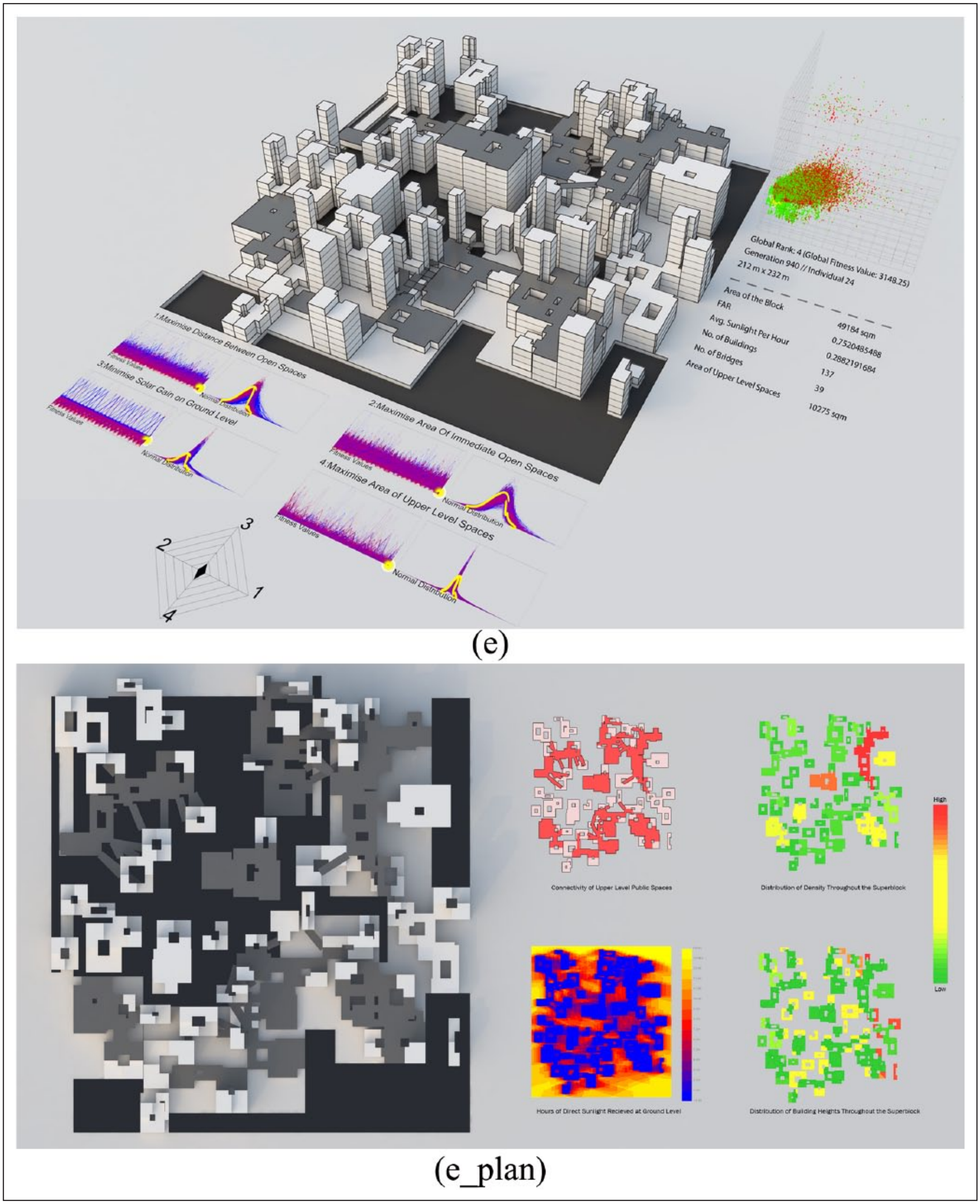


Figure 19. (a–e) The five highest globally ranked solutions. The normal distribution graphs present the distribution of all generations within the population, going from blue (earliest generation) to red (latest generation). The generation that each solution lies within is highlighted in yellow.

To examine these individuals thoroughly, each solution is accompanied by several statistical and analytical graphs that present the distribution of the fitness values as well as the ‘position’ of each individual within the overall population. The graphs are complemented with the search space for the full simulation (in contrast to only a selected generation presented earlier) as well as a detailed view of the morphological properties of each solution (Figure 19). The 5 phenotypes presented display the simulations ability to evolve a highly integral morphological distribution of ground level and upper level public space, connected skyways and a variation in the distribution of density throughout the superblock. However, the applied selection method of the ‘global rank’ favoured a set of solutions that shared similar properties; thus, this selection strategy is currently being revised to ensure more variation is achieved among the selected solutions (the solutions visualised in Figure 10 present the fittest solution for each fitness criteria; as such, and in contrast to the globally ranked solutions, one appreciates the significance of utilising a MOEA when comparing the morphological variation between the fittest solutions for the different fitness objectives). However, in an attempt to directly control variation across the simulation, further research conducted by the authors examines the benefits of incorporating a population-based fitness criterion as a fitness objective to direct the diversity of solutions throughout the simulation and gain greater control over the degree of variation and convergence within the population[47].

Conclusion

The presented experiments demonstrate the advantages of the application of an adaptable model, driven by a generative evolutionary design tool, to generate morphological variation evolved in response to conflicting criteria, thus increasing the potential of the urban fabric to adapt and cope to changes in environmental and climatic conditions. In contrast to the traditional design process of perfecting a single unique design solution, the applied model employs a process of ‘evolving’ varied populations of context-specific morphologies, allowing for greater variation of morphological attributes throughout the urban fabric, thus moving away from the ‘universal city’ of the 20th century to one that is better equipped to the rapid environmental and climatic challenges of the 21st century.

The application of MOEAs as a problem solver has been proven to be an advantageous approach for complex problems across a range of different disciplines as well as a multitude of scales. In design, the potential of evolving a population of design solutions that vary in morphological diversity is central for problems that do not have a single optimal solution; this is especially the case when the end user of the proposed design is not limited to a single individual or group of individuals, rather a population of individuals that all hold a stake in the final output. As such, the degree of variation generated when utilising MOEAs is essential for allowing greater flexibility when responding to the fitness objectives driving the design experiments. However, unlimited variation serves very little purpose, but when coupled with optimisation, the evolved solution set is a robust and powerful alternative to a single, preference-based approach.

What becomes critical is attaining dynamic control over the variation or convergence of the population in response to a dynamically changing environmental context, one where the fitness level of the population is utilised as a fitness criterion that modifies the levels of exploration or exploitation of the fitness landscape. In addition, the criteria specified for selecting the final solutions at the end of the simulation is equally critical; objectivity must be maintained by limiting the user’s own preference when selecting the final solution set. More importantly, the selection criteria should be independent from the evaluative criteria driving the algorithm; this allows for additional variables to be considered that are not contingent on the simulation. The authors are currently conducting research into ‘hardcoding’ within the genotype of each individual additional variables that may be later called upon during selection, in addition to incorporating a population-based fitness criterion to control the degree of variation among the population; although the computational load for this is minimal, its practicality becomes highly beneficial when attempting to develop an adaptable model that can be utilised by more than one user across a range of different environmental and climatic conditions.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship and/or publication of this article.

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