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RESEARCH ARTICLE

# Application of homeostatic principles within evolutionary design processes: adaptive urban tissues

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## Abstract

Nature is a repository of dynamic and intertwined processes ready to be analyzed and simulated. Homeostasis, as a scale-free and universal biological process across all species, ensures adaptability to perturbations caused by intrinsic and extrinsic stimuli. Homeostatic processes by which species maintain their stability are strongly present through ontogenetic and phylogenetic histories of living beings. Forms and behaviors of species are imperative to their homeostatic conditions. Although biomimicry has been established for many decades, and has made significant contributions to engineering and architecture, homeostasis has rarely been part of this field of research. The experiments presented in this paper aim to examine the applicability of biological principles of homeostasis into generative design processes in order to evolve urban superblocks with a degree of morphological and behavioral adaptation to environmental changes; the objective is to eventually develop a modus operandi for the design and development of cities with embedded dynamic adaptation attributes.

*Keywords:* architecture; urban; homeostasis; evolutionary computation; biological principles; adaptation

## 1. Introduction

Rapidly changing environmental and climatic conditions, coupled with the growing numbers in urbanized populations, have stressed the ability of existing cities to cope with these sudden and highly impactful changes. The critical threshold of stability (Weinstock, 2010) in which a city's population grows beyond its maximum capacity, thus straining its resources and ecological demand, transforms the city to one that is highly sensitive to changes in its environment. Although this is a scenario that has repeated itself multiple times across different geographic locations and time periods, its occurrence in modern day carries dire impacts as the current rate of change to climatic and environmental conditions is one that is unprecedented. The adaptation of cities that have approached their critical threshold is highly contingent on the rate of change in the environment; historically, the rate of environmental and climatic changes allowed for cities to evolve in response to these changes. However, the rate of environmental and climatic changes observed in the 20th century, as well as predicted throughout the 21st century, coupled with the exponential rate of population growth (including the migration of people from rural settlements to urbanized ones) highlights the necessity to re-evaluate the city's ability to maintain a balanced relationship between the internal processes that govern the city's growth and development and its environment. The ever-increasing computing powers in the field of architecture and design have enabled the generation of design options within different simulated scenarios in which environmental conditions are at their extremes. Therefore, variables directly driven by environmental changes affecting urban settlements—such as extreme climatic conditions—must be embedded into the design processes from its initial stages in order to generate architectural solutions with a degree of morphological and behavioral adaptation to such changes.

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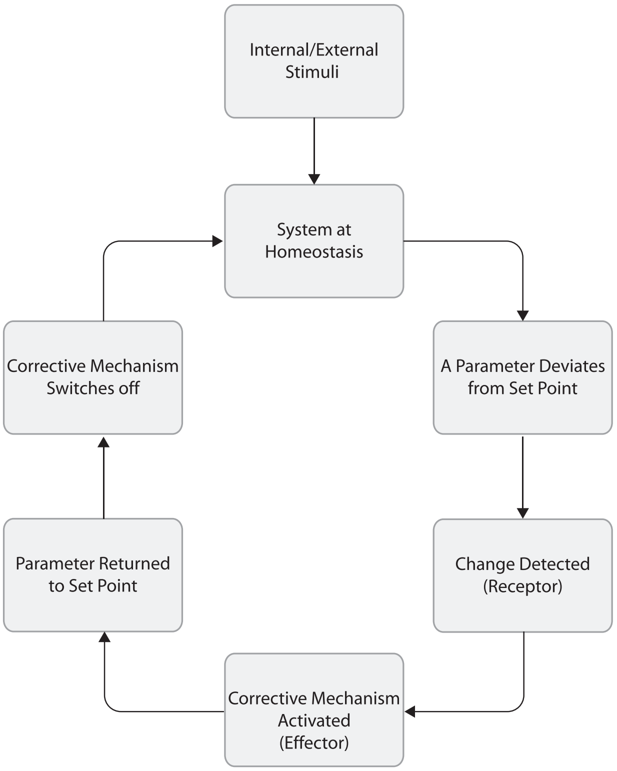


**Figure 1:** Principles of a homeostatic process.

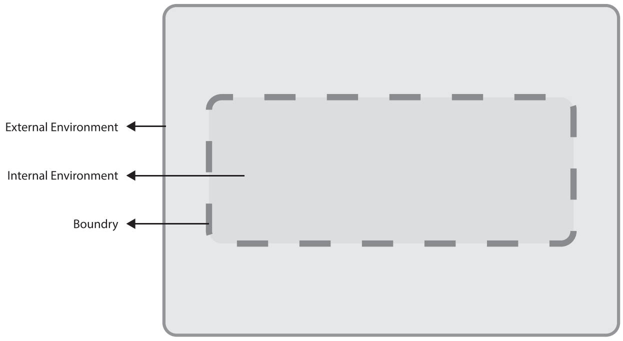


**Figure 2:** Spatial domains. Interconnected relationship between internal environment, external environment, and the boundary by which they are separated.

## 2. Homeostasis in Nature

In biology, an organism's longevity is contingent on the metabolic processes actuating change within the organism in response to its local environment (Faraud, 2017). These metabolic processes are the driving force of life across a range of scales, from "molecular to the intricate dynamics of ecological systems." Michael Weinstock, in his article "*Metabolism and Morphology*," further explains that "metabolism determines the relations of individuals and populations of natural forms with their local environment" (Weinstock, 2008, p. 27). Through time, species have evolved highly efficient processes of maintaining their metabolism within a stable range, allowing for their adaptation to external environmental pressures, which in turn affects the "homeostasis" of an organism [the term originally coined by Cannon (1932)], in which it is able to maintain a state of equilibrium through perturbations caused by intrinsic and extrinsic stimuli. According to J. Scott Turner, homeostasis is not an outcome rather a process; a "simple steadiness on internal environment (the outcome) is not sufficient evidence for homeostasis" (Turner, 2002, p. 192). Turner further clarifies that "to qualify as homeostasis, a system should display the signs of that process in operation—ideally signs that are independent of the context within which it is working" (Turner, 2002, p. 192).

As such, homeostasis is a process by which all species and their constituent subsystems are continuously being adjusted to both internal and external changes. Alvin Nason, in his textbook "*Modern Biology*," refers to it as a "remarkable" ability of almost all animals to maintain their stability through extreme changes (Nason, 1965). While John S. Torday, in his article "*Homeostasis as the Mechanism of Evolution*," claims that not only does homeostasis assure equilibrium of a biological organism, "but also provides the reference point for change if necessary, for survival in an ever-changing environment" (Torday, 2015, p. 574). Therefore, each disturbing force by which a biological system is induced to stay out of equilibrium results in a "call for action" to neutralize its effect. More complex systems, however, require more complicated regulatory processes to achieve a steady state (Nirmalan & Nirmalan, 2017). Nonetheless, the fundamental principles of all homeostatic processes comprise three important components: (i) a set point, (ii) receptors, and (iii) effectors, whereby a controlled variable is preserved around the set point, which in turn achieves homeostasis. Any changes to the controlled variable caused by either internal or external stimuli will be detected by a receptor or receptors. If the controlled variable deviates beyond an organism's acceptable range, an effector (or effectors) will attempt to reverse the direction of the stimuli to adjust the variable back to the set point (Rye et al., 2017) (Fig. 1).

The main goal of any homeostatic process is to neutralize the effects of external stimuli. Whether through the application of negative or positive feedback loops within the organism's subsystems, it is this balance within the organism that allows it to efficiently adapt and survive when faced with sudden and highly impactful changes to its environment.

### 2.1. Homeostatic principles

Gerlee et al., in their article "*Evolving Homeostatic Tissue Using Genetic Algorithm*," state that homeostasis is a significant property of any living being, one that "involves the ability to self-regulate in response to changes in the environment in order to maintain a certain dynamic balance affecting form and/or function" (Gerlee, Basanta, & Anderson, 2011). This self-regulation through homeostatic processes occurs at multiple levels within all species and regulates a wide range of controlled variables. One such variable, which is examined in the presented experiments, is that of heat and energy, and the possible contribution of regulatory processes in generating environmentally driven urban form with embedded homeostatic attributes.

In this context, the homeostatic process of *thermoregulation* is highlighted, in which the exchange of heat between a biological organism and its local environment is controlled. This exchange can be performed through four mechanisms: radiation—the emission of electromagnetic heat waves from any dry surface; evaporation—the dissipation of heat from a given surface caused by evaporation; convection—the removal of heat through air currents; and conduction—the transfer of heat through direct contact (Rye et al., 2017).

In addition to the above, thermoregulation is further categorized into two distinct processes: **endothermic** and **ectothermic**. Endothermic species (or endotherms) have highly efficient internal thermoregulatory processes by which they maintain their temperature within a narrow range; however, in the case

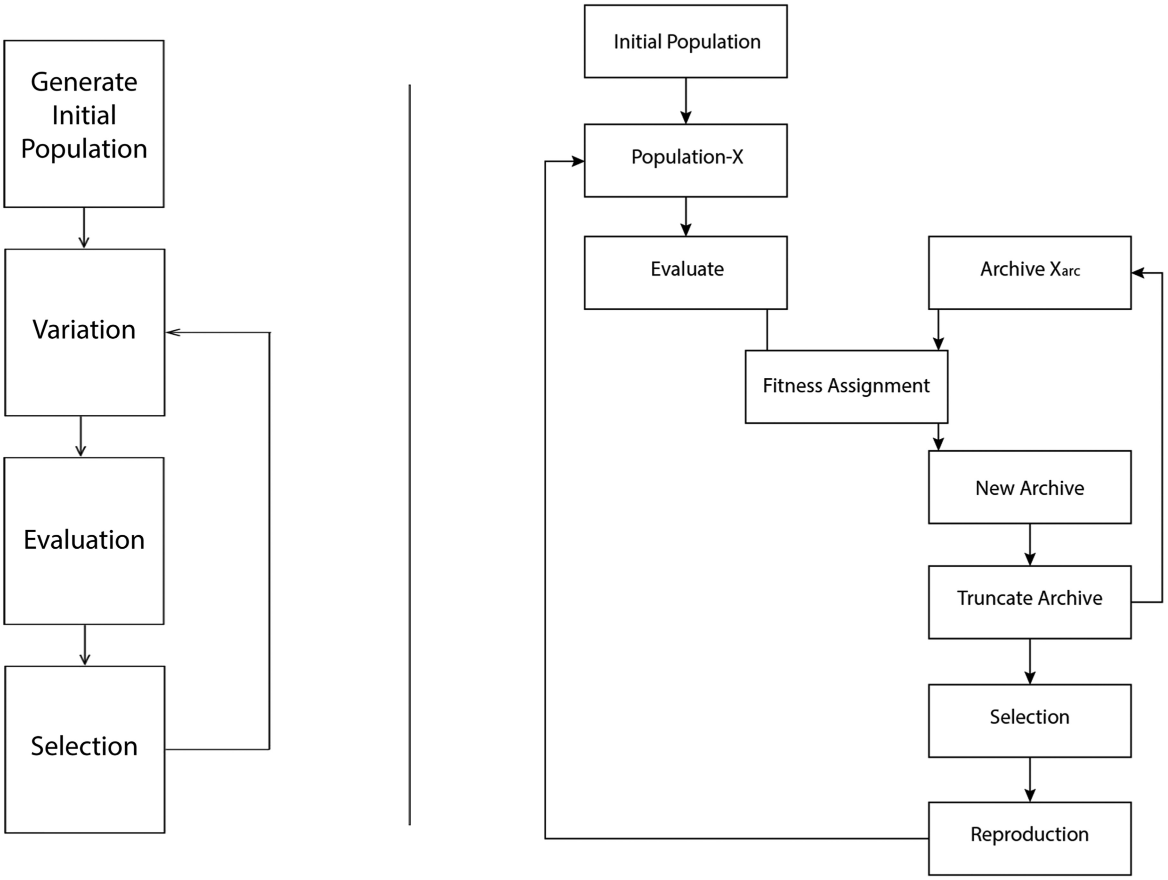


**Figure 3:** Evolutionary algorithm. Comparison between the basic principles driving most evolutionary algorithms (left) with the modified algorithmic workflow developed (and continuing to be developed) within evolutionary computation (right; diagram represents the algorithmic workflow of the SPEA-2 algorithm).

of ectothermic species (or ectotherms), their internal temperature fluctuates within a wider range that is mostly regulated through behavioral changes rather than internal processes. Endotherms take advantage of their internal physiological processes and morphological characteristics to maintain their homeostasis. On the other hand, ectotherms primarily rely on their behavioral patterns, individually or collectively, to maintain their homeostasis. In this context, the presented experiments aim to utilize endothermic and ectothermic principles toward evolving urban form that is adapted to its environmental context.

## 3. Relevance in Design

In architecture, nature has often been considered a source of both formal and metaphorical inspiration. However, the contemporary reconfiguration, as reflected in the differences between the revised and original editions of Steadman, 1979 "*The Evolution of Designs: Biological Analogy in Architecture and Applied Arts*," has changed the idea of nature from a formal metaphor to a repository of interconnected dynamic processes available to be analysed and simulated. The pursuit of deeper insights between biological processes and architecture has accelerated over the past two decades for multiple reasons, most prominent of which was the belief that architecture must be driven by the systems and processes inherent to the biological system, rather than being a morphological imitation of the organic form (Steadman, 2008).

Understanding the emergent properties of natural systems have changed the application of their principles within architecture from top down to buttom up; in which the systems are approached as bottom-up processes that are aggregations of multiple components striving to maintain their equilibrium; from the peer-to-peer communications at a cellular level to the emergent social behaviors that result from them. According to Turner, when understanding the complex and emergent behaviors of natural systems, design principles extracted from these systems have changed the role of architects from "specifiers" to "facilitators" (Turner, 2002). As such, the emergence of forms and behaviors through generative design processes is not solely a product of the decision made by the architect in charge, rather it is coupled with outcomes of simulated interactions of design components developed in the early stages of design. Therefore, the application of such principles at larger scales, such as designing cities, induces their form and operation to be in favor of the homeostatic imperatives of its constituent components.

Although homeostasis is a fundamental biological process among all species across a range of scales, these processes operate within a spatial domain defined by three phenomena: internal environment, external environment, and a boundary by which they are divided (Fig. 2). These spatial domains are confined differently within the context of each regulatory process

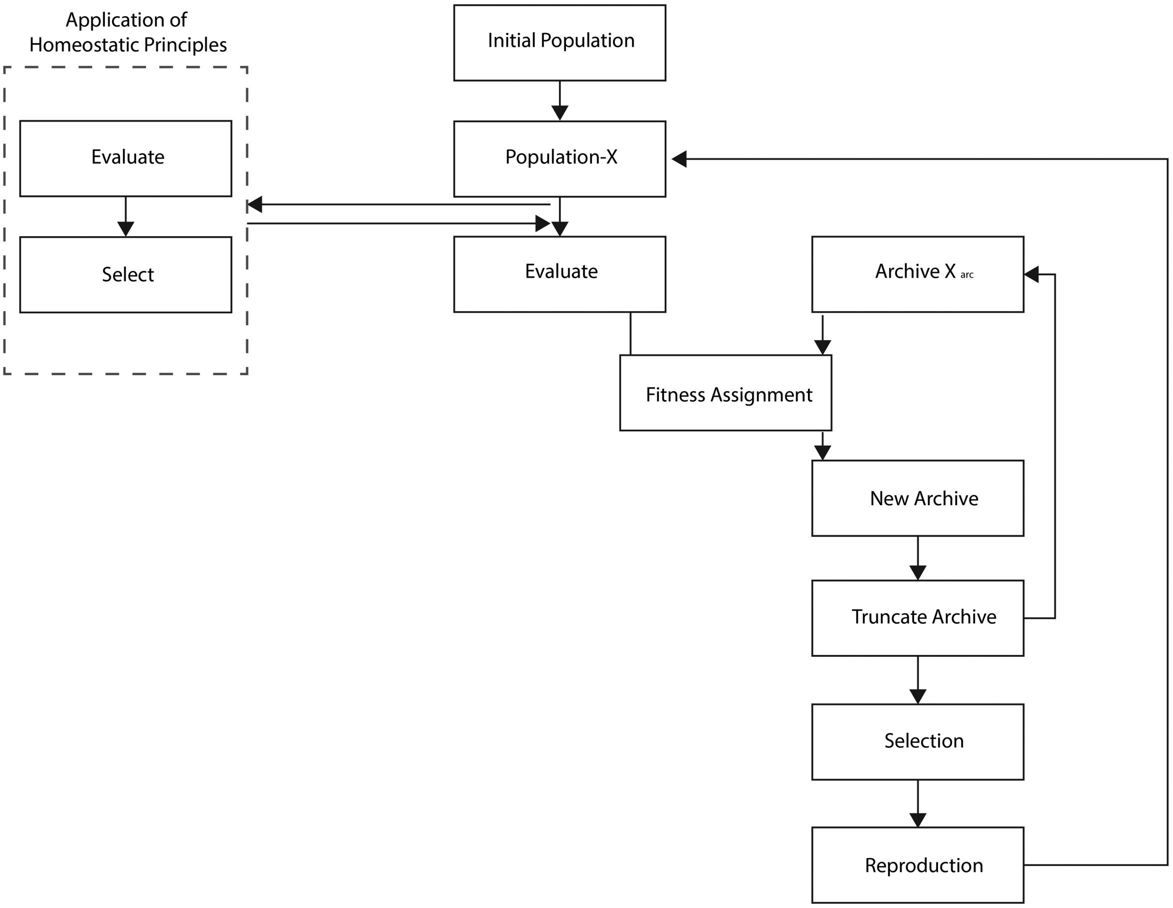


**Figure 4:** Customized evolutionary algorithm. Incorporation of homeostatic principles (secondary evaluation and selection mechanism) into the SPEA-2 algorithm.

**Table 1:** The parameter values and a short description of the algorithm settings.

| Parameters | Short description | Value |
|---|---|---|
| Elitism | Number of solutions selected from the archive to breed | 0.5 |
| Mutation probability | The likelihood of a gene to mutate | 0.2 |
| Mutation rate | The intensity of the mutation applied to the gene | 0.9 |
| Crossover rate | The likelihood of two solutions to exchange genes | 0.8 |
| Population size | Number of solutions in each generation | 25 |
| Generation size | Number of generations in the simulation | 300 |

and in some cases go beyond of what is conventionally known to be the “boundary” of a species.

Although biomimicry has been established for many decades, and has made remarkable contributions to many disciplines, homeostasis, a crucial biological process, has rarely been part of this field of research, especially at an urban scale. Homeostasis as a universal and scale-free biological process may yield useful methods and strategies to architects and designers to generate singular and collective architectural assemblies with significant environmental performance. The spatial and functional relationship among the different elements of a city creates a unique opportunity to test the application of biological homeostatic principles at an urban scale.

Historically, the evolution of cities was driven by the adaptation of urban form in response to a narrow range of change in its environmental context. However, changes in environmental and climatic conditions witnessed throughout the last century due to the exponential growth of both population and industry are occurring at a more frequent and rapid rate, within a wider range and higher intensities. This paper tries to incorporate the principles of thermoregulation in species into a generative design process in order to evolve urban blocks adapted to a simulated set of environmental conditions. The experiments compare utilizing the main principles of endothermic adaptation (adapting the narrow range of change) and ectothermic adaptation (adapting to a wider range of changes) to examine their applicability in designing urban form. The aim is not to simulate the behavior of organisms, rather to use their principles of adaptation and map them into a design model applicable for an evolutionary design process. Given the rapid changes in climate, cities with morphological attributes

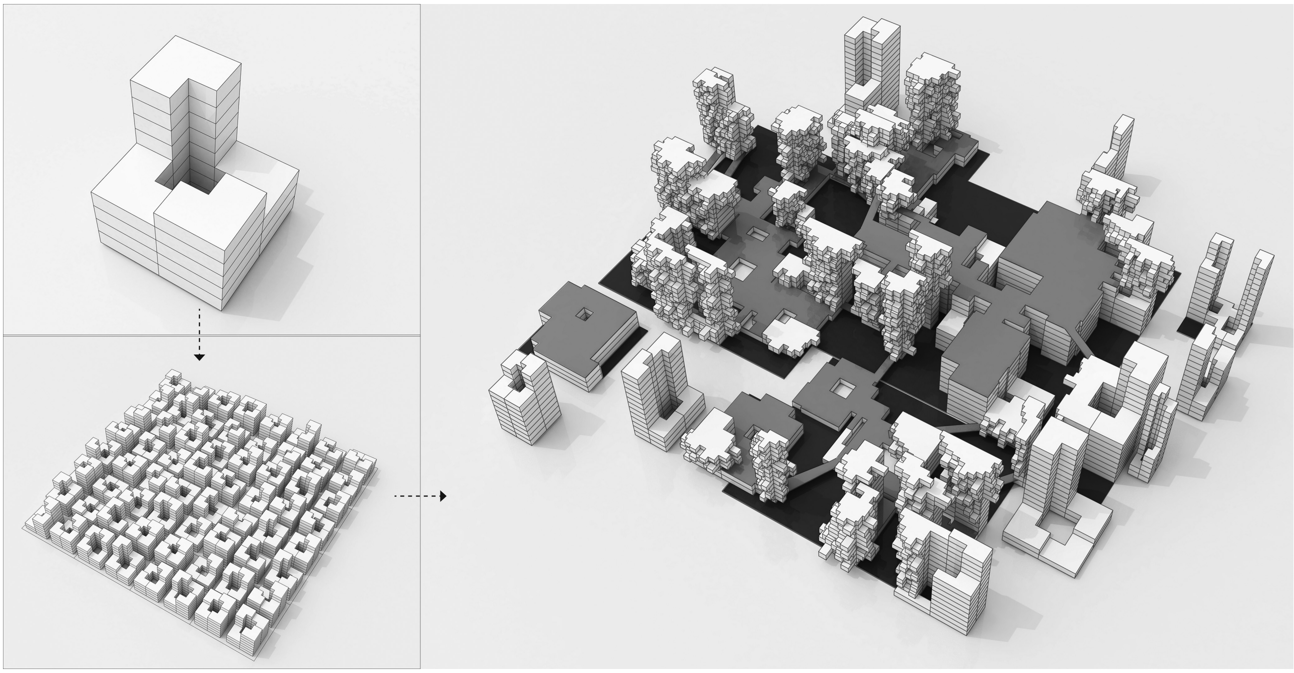


**Figure 5:** The primitive in this experiment is built upon the primitive used in Makki et al. (2018) but with further morphological attributes (applied and developed from Fig. 6) in order to facilitate endothermic and ectothermic thermoregulation processes to regulate the proxy value.

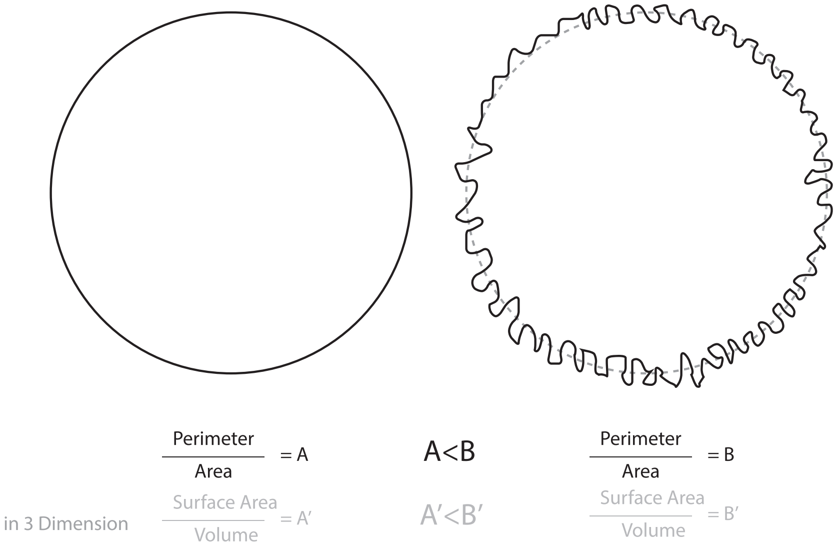


**Figure 6:** Morphological attributes assisting homeostasis. An abstract representation of the skin's morphological traits found in several species (right). The increased surface area allows for heat to dissipate (as well as increase self-shading) when compared to a boundary without this morphological trait (left).

adapted to a wider range of climatic conditions may be more advantageous to their survival through extreme environmental changes.

## 4. Computational Platform

The application of biological homeostatic principles for the development of urban form requires a responsive generative model that incorporates within it a feedback mechanism that allows for the evaluation, selection, and reconfiguration of the generated design solutions. As such, the presented experiments utilize an evolutionary biological model that aims to replicate and apply the basic evolutionary principles of variation, evaluation, and selection to generate a population of candidate design solutions that strive to increase their "fitness" toward defined environmental objectives (Luke, 2013). Parameters for which homeostasis should be maintained and monitored are being introduced to the experiment as fitness objectives enabling their

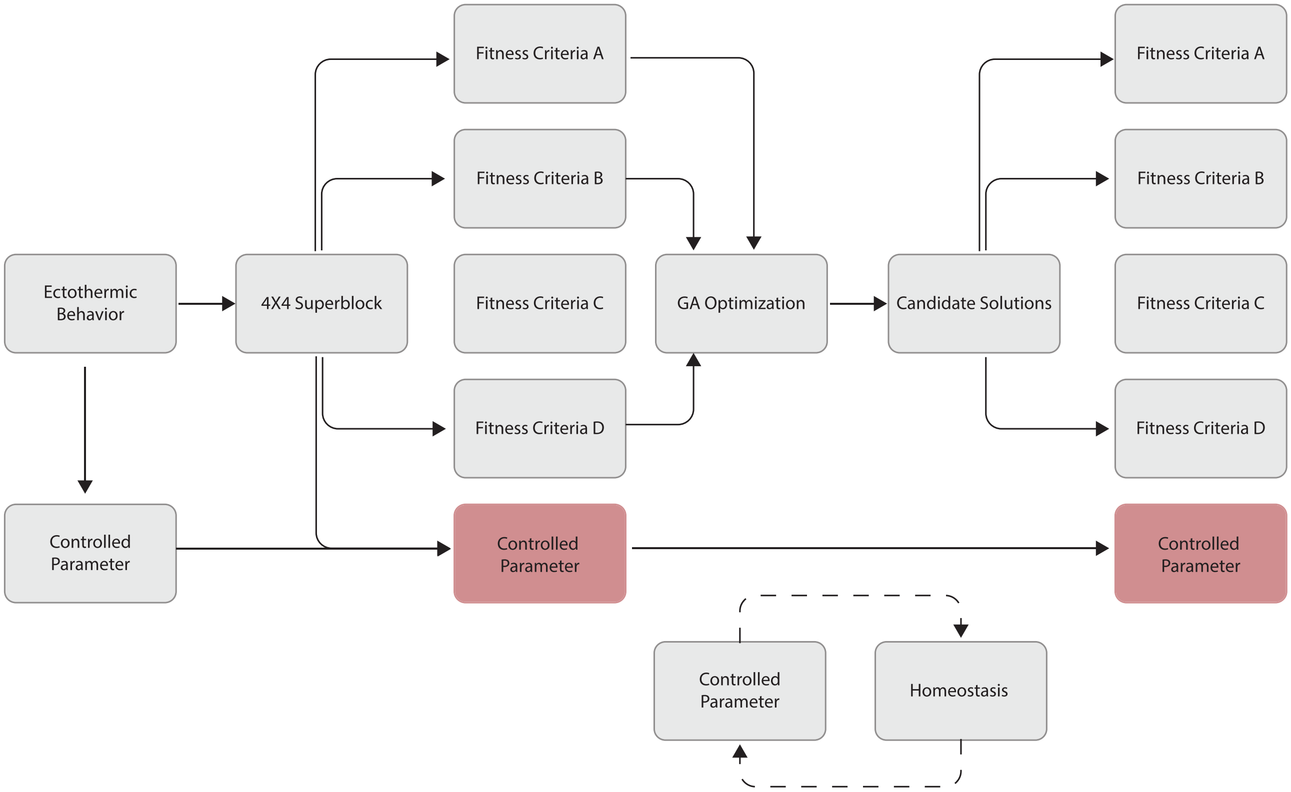


**Figure 7:** Ectothermic experiment pseudocode. Pseudocode for the ectothermic experiment. The correcting mechanism (homeostatic process) is not a part of the generative process. This simulation tends to study the effects of specifying fitness objectives in driving the simulation to produce more homeostatic solution without hardcoding (imitation of internal process) a correcting mechanism into the system.

evaluation and selection; as such, homeostatic principles will be inserted to the conventional algorithmic loop of an evolutionary simulation through introducing an additional evaluation mechanism.

In its simplest form, an evolutionary model is best described as a two-step process of random variation within the genome of a phenotype, and the selection of said phenotype through environmental pressures (Mayr, 1988). This forms the basis of most evolutionary algorithms such as the NSGA-II algorithm (Deb, Agrawal, Pratap, & Meyarivan, 2000) and the SPEA-2 algorithm (Zitzler, Laumanns, & Thiele, 2001) in which the developed algorithmic setup is formulated through the basic looped process of generating an initial population of competing random solutions, modifying the solutions through random variations, evaluating the solutions through an objective performance measure, and finally, selecting some solutions while discarding others through a predefined selection mechanism (Fogel, 2008) (Fig. 3).

As such, the feedback mechanism is highly dependent on the evaluation and performance measure, which ensures that the generated solutions are responsive to the fitness objectives driving the simulation. More importantly, this allows for (with a slight variation to the algorithmic setup) the incorporation of Boolean conditions that allow for a secondary evaluation and selection process to run within the algorithm (Fig. 4). In the context of the presented experiments, the Boolean conditions imposed to generate the secondary evaluation and selection process are utilized to incorporate homeostatic principles within the simulation, aiming to drive the simulation toward generating design solutions that display homeostatic behaviors by maintaining their fitness properties (and consequently their morphological traits) within a defined range. Even though external environmental pressures may attempt to generate solutions that lie out of this range, the homeostatic Boolean operations aim to counteract this through regulating the genomes of the generated solutions throughout the simulation.

The presented experiments utilize the multi-objective Strength Pareto Evolutionary Algorithm 2 (SPEA-2) developed by Zitzler et al. (2001) as the base algorithm into which the simulation is developed. The grasshopper add-on “Octopus” (Octopus, 2013) is used to run the simulation, while the grasshopper add-on “*Wallacei*” (Wallacei, 2018) is used to analyse the results. In all of the conducted experiments, the algorithmic parameters within the evolutionary simulation were set to the following values in Table 1 [for a detailed description of the terminology used in the simulation, see Makki, Navarro, and Farzaneh (2015, p. 5)].

## 5. Experiments

The computational setup for the design experiments has been developed according to the complexity of the homeostatic principle being investigated. As such, the experiments aim to understand, analyse, and incorporate the principles of

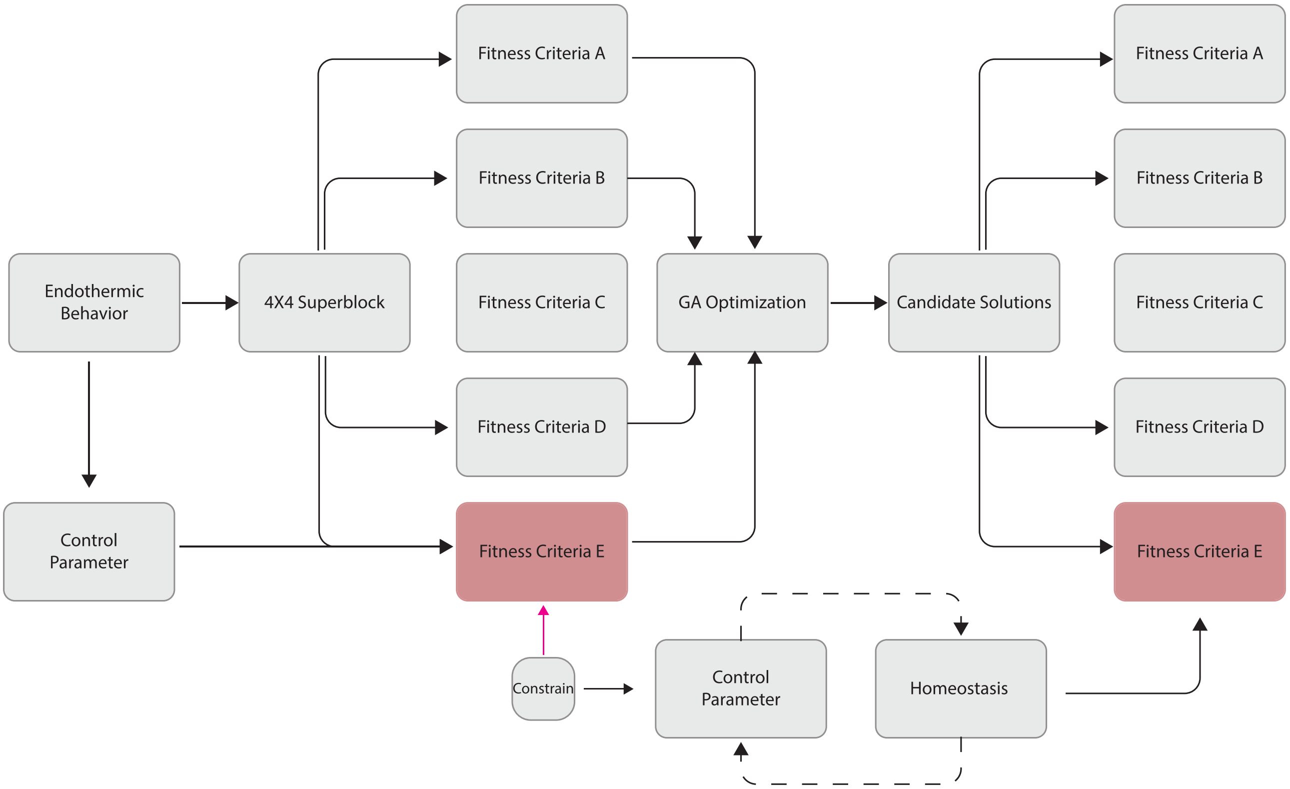


**Figure 8:** Endothermic experiment pseudocode. Pseudocode for the endothermic experiment. This experiment tends to study the effects of hardcoding a correcting mechanism (homeostasis) into the simulation.

thermoregulation into the generative process of producing a population of urban superblocks that optimize for multiple conflicting objectives. The selected primitive geometry is an urban superblock extracted from the City of Fes in Morrocco (Fig. 5) [the selection of this specific superblock is in line with previous research conducted by the authors that investigates the Fes superblock in great detail; for more information about the superblock and the research behind it, please see Makki, Showkatbakhsh, Tabony, and Weinstock (2018)]. In the context of this paper and for the purpose of the precise analysis of data outputted by each simulation, solar radiation is the only means by which heat can be dissipated or conserved. Thus, the presented experiments examine the effects of solar radiation on the surfaces of the primitive geometry as well as its regulation.

The experiment is conducted in two parts, to study, analyse, and simulate "Endothermic" and "Ectothermic" thermoregulatory processes and behaviors through evolutionary simulations to evolve design solutions with embedded homeostatic principles (Figs 7 and 8).

## 5.1. Incorporation of the selected homeostatic principle into the generative design process

The urban patch in the context of these experiments is comprised of various components with multiple parameters that are to be maintained at homeostasis. However, for the purpose of the experiments presented, elevated open spaces, one of the constituent components of this urban morphology, are being investigated. A proxy value as a controlled variable (the parameter that needs to be maintained at homeostasis) was introduced to the existing computational setup.

In the experiments presented in Makki et al. (2018), the contribution of elevating the open spaces throughout the urban patch was examined in order to address problems such as maintenance of sufficient amount of open spaces with diverse spatial qualities while increasing density in the city fabric. With respect to the morphology of the selected primitive, in the context of this paper, a controlled variable derivative from the elevated open spaces has been defined to study the effect of application of a secondary evaluation, inferred from principles of homeostasis, into the generative design process.

The controlled variable in the experiments is the ratio of shadow to solar gain ($\beta = \frac{Shadow}{Solar\ radiation}$) on the selected elevated open spaces ($\alpha$) (Figs 9 and 10). If a building or buildings to which an elevated open space is attached are taller than the elevated open space, the elevated open space is going to be selected for the calculation of proxy value $\beta$ and named ($\alpha$) in the experiment. Essentially, ($\alpha$) surfaces are the constituent components of the generated urban patch at which homeostasis is going to be studied; thus, $\beta$ needs to be maintained throughout the simulation run. In the experiment utilizing endothermic principles, $\beta$ is supposed to be maintained within a controlled (and smaller) range while in the experiment utilizing ectothermic principles it will fluctuate within a larger range.

The computational setup was further modified to facilitate morphological changes to assist controlling of $\beta$, in other words, homeostatic processes. If the amount of solar gain of the building surfaces within a falloff area of $\alpha$ surfaces is larger than 60% of full possible sun exposure to those surfaces, protrusions will

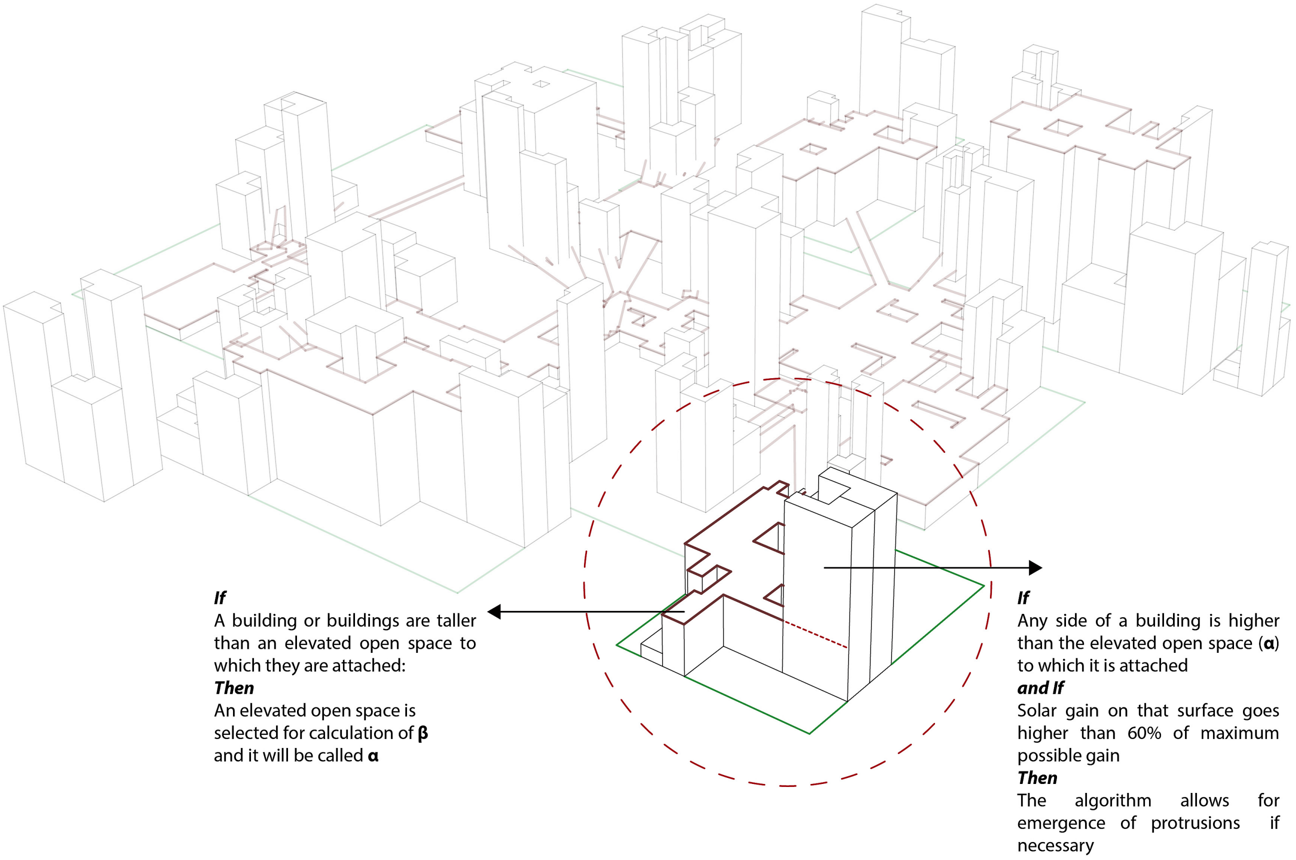


**Figure 9:** Calculation of the proxy variable $\beta$.

emerge from those building surfaces should the algorithm favor such solutions (Figs 9 and 10). The emergence of protrusions tends to (i) decrease the solar gain on the building surfaces by self-shading, and (ii) cast shadow on $\boldsymbol{\alpha}$ surfaces to maintain homeostasis of $\boldsymbol{\beta}$.

## 5.2. Selection of the fitness criteria

Two simulations were conducted to simulate and study homeostasis (Figs 7 and 8). The ectothermic experiment (experiment 1) was conducted with four fitness criteria, none of which are directly regulating $\boldsymbol{\beta}$. This was chosen to imitate behavioral adaptation, while the endothermic experiment (experiment 2) was conducted with an additional (fifth) fitness criterion to study means of implementation of homeostatic internal processes (endothermic species take advantage of internal processes to maintain their homeostasis). The fitness criteria for both the experiments are as follows:

a) An increase in the distance between elevated and on the ground open spaces (Fig. 11);
b) A decrease in the sun radiation on emerged protrusions on the building surfaces (Fig. 12);
c) An increase in height difference between elevated open spaces ($\alpha$) and their surrounding buildings (Fig. 13);
d) An increase in shadow on the selected elevated open spaces ($\alpha$).

Each of these objectives is the result of simulating endothermic/ectothermic behaviors into the morphology of the superblock with the aim of maintaining homeostasis of $\boldsymbol{\beta}$. However, the urban applications of the applied fitness criteria are of equal significance; these are as follows:

By increasing the distance between open spaces on different levels, their accessibility from various parts of the superblock is optimized, allowing for greater connectivity to these spaces while simultaneously encouraging verticality rather than horizontality. With finite land available in near future, urban tissues should grow vertically more efficiently than horizontally. Optimizing this value ensures variation in height within the superblock by which the possibility of casting shadow on $\boldsymbol{\alpha}$ surfaces will increase (Fig. 11). This objective aligns with the idea of behavioral changes in ectothermic species, i.e. changes in morphology in order to facilitate the control over the $\boldsymbol{\beta}$ value.

A set of genes is applied to the experiments in order to emerge protrusions on buildings to which $\boldsymbol{\alpha}$ surfaces are attached. Protrusions emerge in response to excessive solar radiation on building surfaces to decrease the solar radiation on surfaces as well as create more shading on $\boldsymbol{\alpha}$ surfaces. By driving the simulation to decrease solar radiation on emerged protrusions, it will be directed toward eliminating unnecessary protrusions (Fig. 12).

By increasing height difference between buildings and $\boldsymbol{\alpha}$ surfaces to which they are connected, the simulation will be optimized toward solutions in which buildings cast adequate shadow on $\boldsymbol{\alpha}$ surfaces to maintain homeostasis of $\boldsymbol{\beta}$ (Fig. 13). Objective D was chosen in coordination with objective C to give them extra weight in the simulation. Figure 14 summarizes the

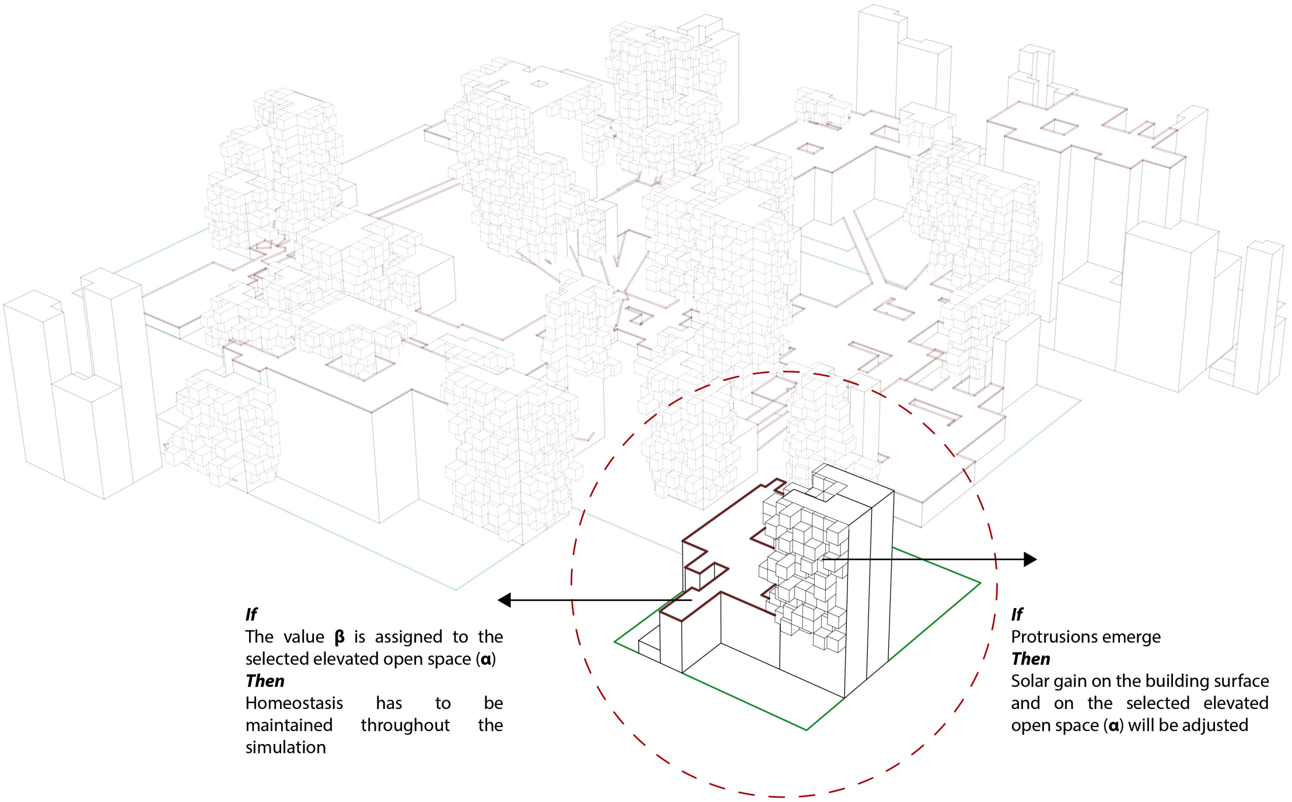


**Figure 10:** Calculation of the proxy variable $\beta$. This figure (together with Fig. 9) shows the calculation of proxy variable $\beta$ and additional morphological attributes added to the existing computational setup. If an elevated open space is selected for the calculation of $\beta$ then that surface is named $\alpha$ throughout this experiment.

experiment setup by highlighting the relationship between the genes, fitness objectives, and morphological attributes of the primitive geometry.

The fifth fitness criterion was introduced to the simulation to imitate an internal process for the endothermic experiment (experiment 2). The fifth fitness objective was solely mathematical to directly act as a regulating mechanism for proxy variable $\boldsymbol{\beta}$. It is as follows: *e*) a decrease in the absolute value of subtraction of $\boldsymbol{\beta}$ from the upper limit of 2 and the lower limit of 1.5 ($E = |\boldsymbol{\beta} - 2| + |\boldsymbol{\beta} - 1.5|$). The endothermic experiment attempts to keep $\boldsymbol{\beta}$ in a controlled and narrow range; in other words, the amount of shadow is set to be between 150% and 200% of the solar gain on $\boldsymbol{\alpha}$ surfaces.

Given the complexity of the design problem, both experiments (endothermic and ectothermic) were limited to 25 individuals per generation with a total simulation runtime of 300 generations (in total 7500 generated solutions). The main purpose of the experiments conducted is to test the possibility and effects of incorporating a homeostatic attribute extracted from thermoregulatory processes into the already existing evolutionary simulation.

## 6. Results

The 7500 genotypes/phenotypes generated by the simulation are each associated with four fitness values per solution in the ectothermic experiment (experiment 1), and five fitness values per solution for the endothermic experiment (experiment 2). The controlled parameter of $\boldsymbol{\beta}$ was recorded throughout both simulations to analyse the performance of each experiment in maintaining its homeostasis. Each experiment was run three times, after which the variance, mean value, and hypervolume indicator of the pareto front for each of the three simulations were recorded and compared (Table 2). The simulation (one from both experiment 1 and experiment 2) with the highest recorded hypervolume indicator was selected for further analysis—the hypervolume indicator compares the space covered by the pareto front of each simulation, attributing greater values to pareto fronts that cover a larger space; for more information on the hypervolume indicator, see Bader and Zitzler (2011).

To ensure a comprehensive understanding of the efficiency of each experiment, a set of analysis was conducted to examine (i) to what extent each simulation could maintain homeostasis of $\boldsymbol{\beta}$; (ii) what is the relationship between the fitness objectives and the controlled parameter $\boldsymbol{\beta}$; and (iii) analysis of homeostatic solutions in both experiments to determine how efficient the employed technique was.

The first analysis performed was to ensure for a unified understanding across the entirety of both simulations. Therefore, the recorded value of $\boldsymbol{\beta}$ throughout both simulations is presented to study how efficient each experiment could maintain homeostasis of $\boldsymbol{\beta}$ throughout the simulation (Fig. 15). The X-axis in Fig. 15 shows the number of generations while the Y-axis is plotting the recorded value of $\boldsymbol{\beta}$ throughout the entire simulation run. The red graph illustrates the fluctuation of the value of $\boldsymbol{\beta}$ in the simulation from the beginning to end. The green indicator in the Y-axis is illustrating the acceptable range in which the value of $\boldsymbol{\beta}$ can fluctuate within. The number of black circles plotted on the X-axis shows the number of individuals

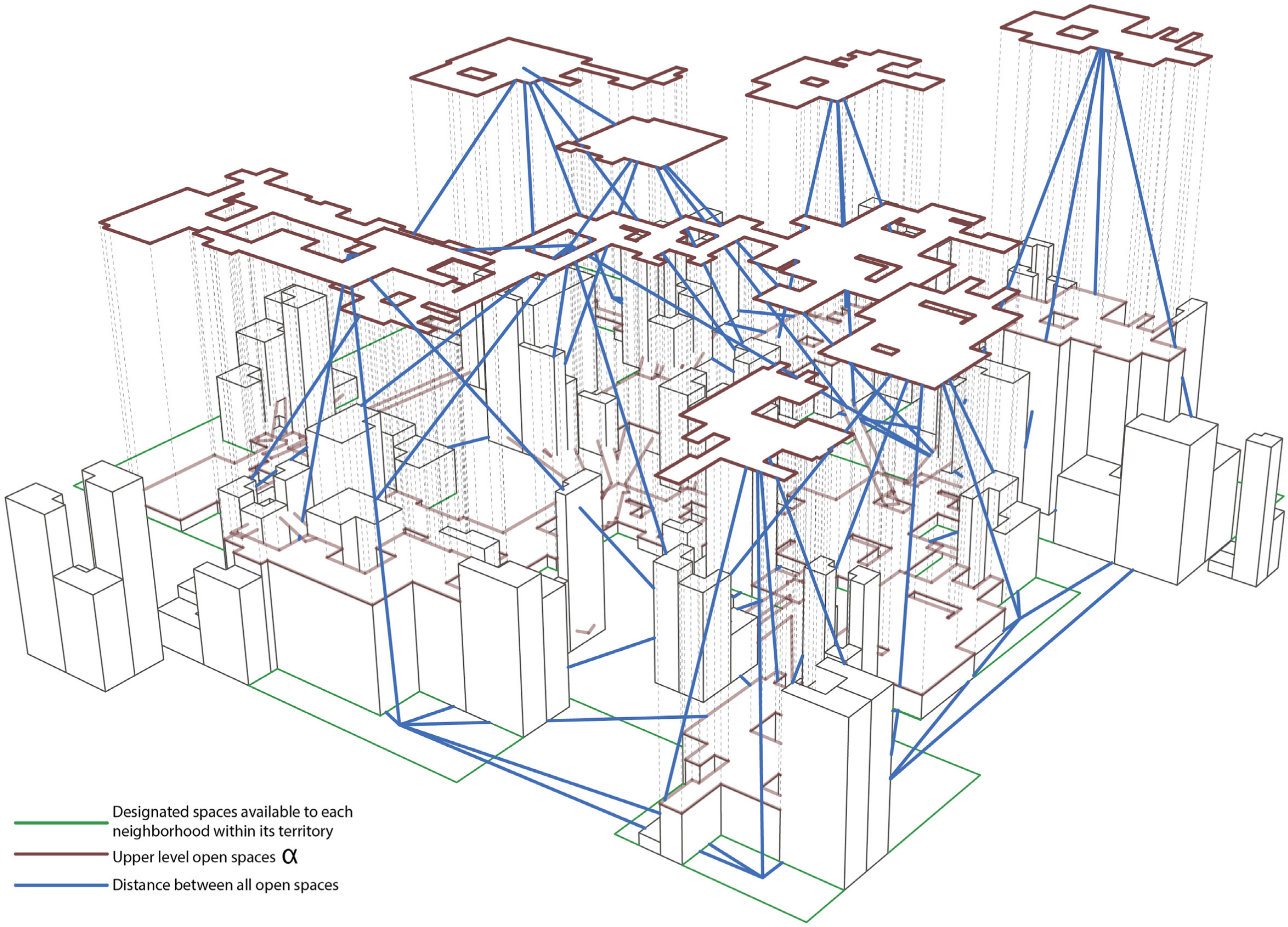


**Figure 11:** Fitness objective A. Increasing the distance between elevated and ground open spaces.

in that generation in which $\beta$ is within an acceptable narrow range.

Recorded data show that the value of $\beta$ ($\beta = \frac{Shadow\ on\ \alpha}{Solar\ radiation\ on\ \alpha}$) throughout the endothermic experiment (experiment 2) fluctuated within a range between 0.0003 and 1520, while in the ectothermic experiment (experiment 1), it oscillated within a larger range between 0.0006 and 1669 (as expected). The endothermic experiment concluded with 756 out of 7500 solutions in which $\beta$ is within the allocated range of 1.5 to 2 (in other words, homeostatic solutions) while 22 out of 300 generations had no homeostatic solutions. Conversely, the ectothermic experiment culminated with 536 homeostatic solutions while producing 56 generations without any homeostatic solutions (Fig. 15).

Studying the overall performance of both experiments presents that the endothermic experiment reached its maximum percentage of homeostatic solutions within 17th generations of the simulation run; it ended with 5% homeostatic solutions. Conversely, the ectothermic experiment arrived at its maximum percentage of homeostatic solutions early on at the 8th generation and after a sudden drop, it ended with 3% homeostatic solutions (Fig. 16).

Comparing the data outputted from both experiments acknowledges the efficiency of the employed technique in the endothermic experiment to incorporate a controlling mechanism to maintain homeostasis of $\beta$. However, solely studying the endothermic experiment does not yield a successful result. Only 5% of the solutions have $\beta$ within the allocated range. This can be a result of other objectives conflicting with the applied controlling mechanism more than expected, thus driving the simulation toward solutions with the value of $\beta$ outside of the desired domain. It signifies the importance of algorithmic setup of the design problem and its objectives. However, it is important to note that, looking precisely at Fig. 15, the endothermic simulation managed to evolve solutions in which the value of $\beta$ oscillates closer to the specified domain while within the ectothermic experiment, $\beta$ oscillates within a larger spectrum.

To understand correlations between controlling mechanisms introduced to the simulation with four fitness objectives, analysis of fitness values was conducted using *Wallacei* (a grasshopper 3D add-on). The software evaluates the numeric data outputted by the simulation and graphically presents the comparative analysis of all the solutions' fitness values within the population. One of the analysis methods generated by *Wallacei* is the parallel coordinate plot, in which every solution's fitness value for each fitness objective is plotted and comparatively analysed, allowing for the user to observe emergent patterns that may have developed throughout the simulation run.

The parallel coordinate plots presented in Figs 17 and 18 represent a comparison of the fitness values of the 7500 solutions for each fitness objective in both simulations. Due to multiple Boolean rules used in both algorithms, some solutions resulted

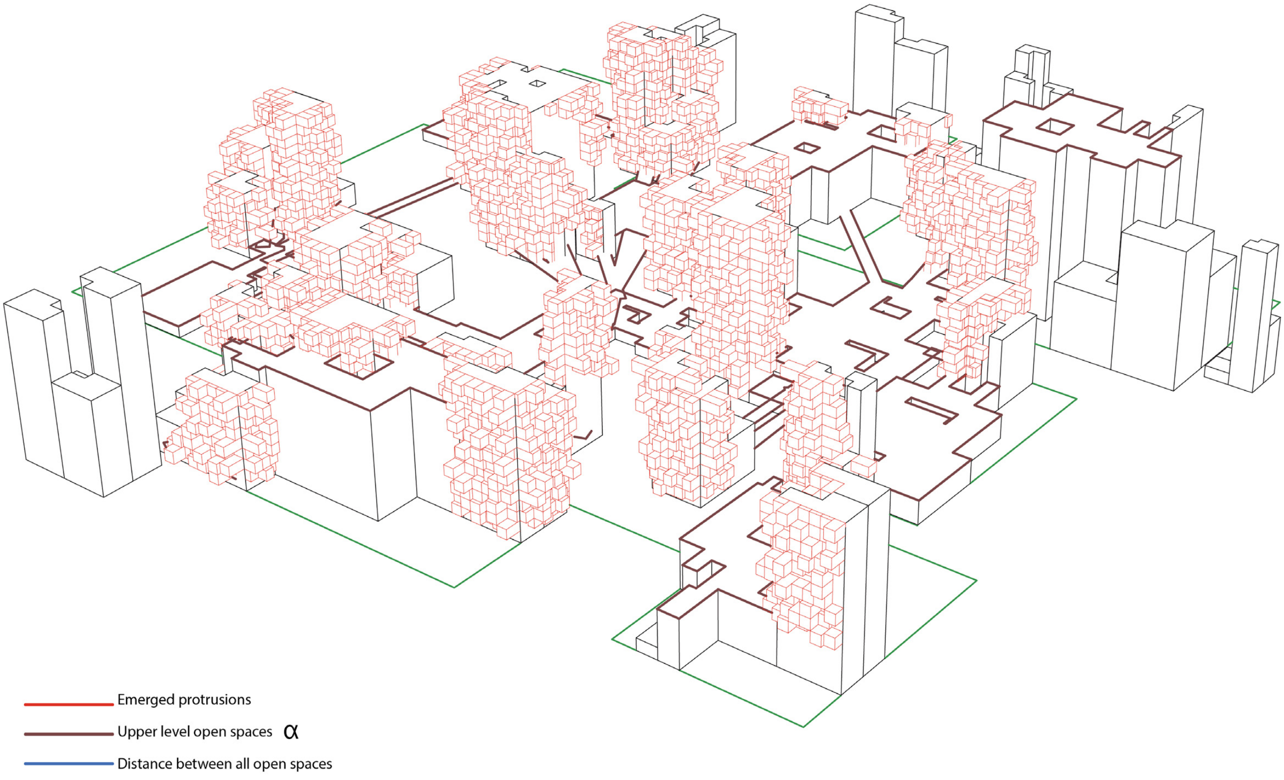


**Figure 12:** Fitness objective B. Decreasing solar radiation on developed protrusions on the building surfaces.

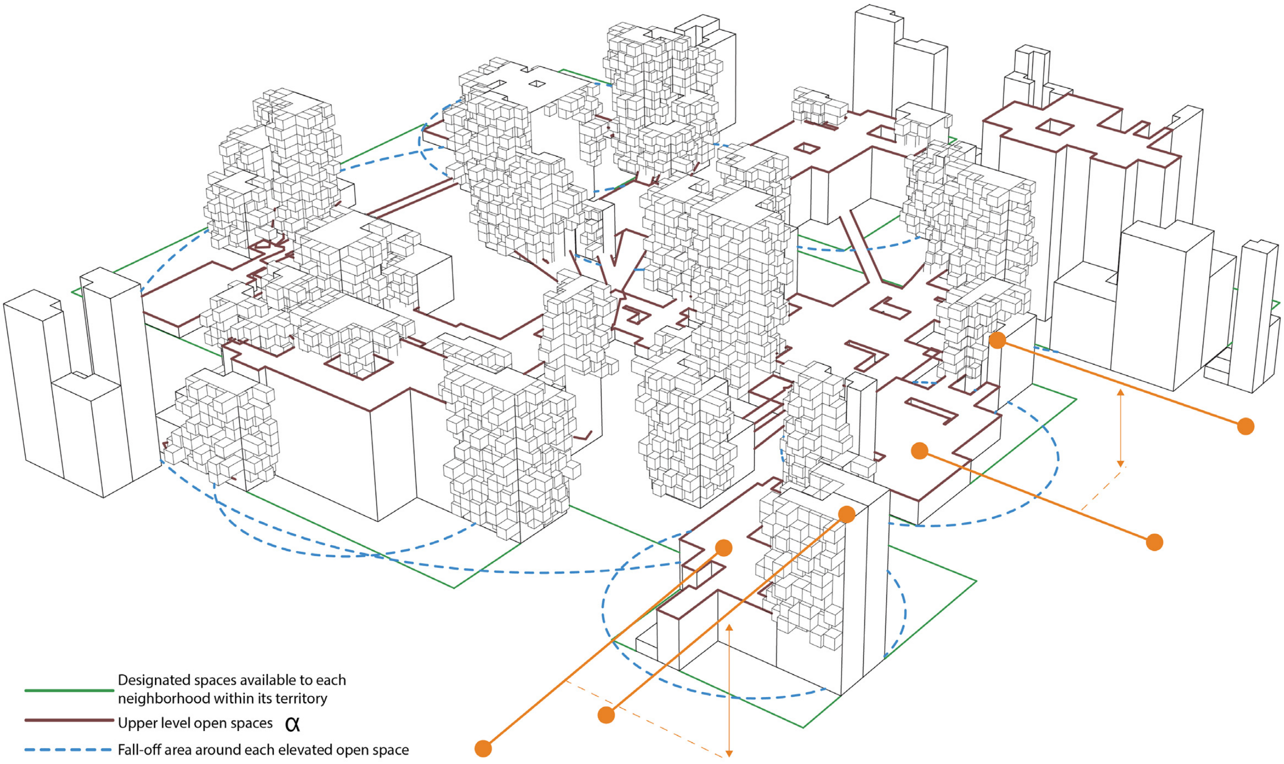
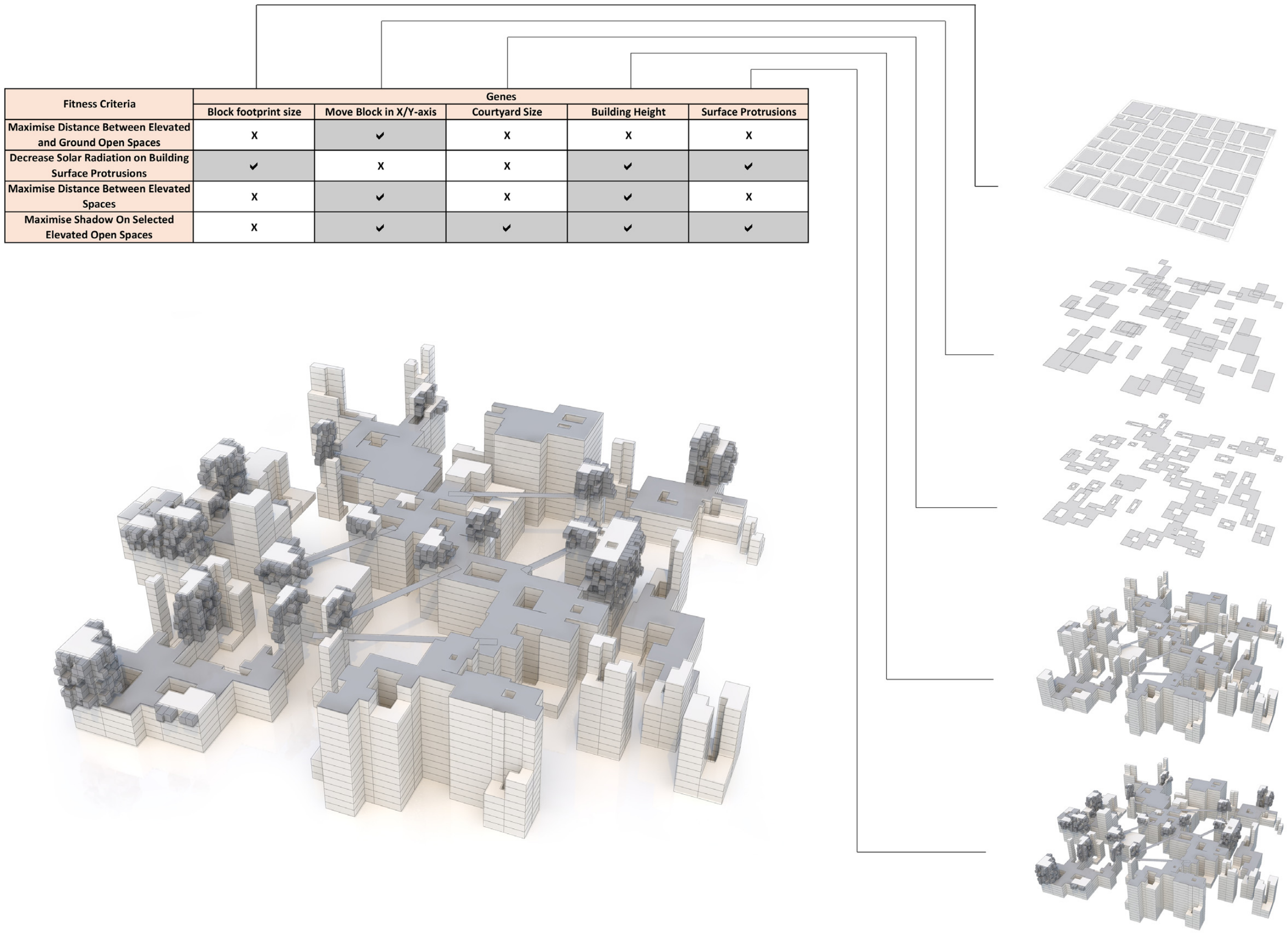


**Figure 13:** Fitness objective C. Increasing height difference between elevated open spaces ($\alpha$) and their surrounding buildings.



| Fitness Criteria | Genes | | | | |
|---|---|---|---|---|---|
| | Block footprint size | Move Block in X/Y-axis | Courtyard Size | Building Height | Surface Protrusions |
| Maximise Distance Between Elevated and Ground Open Spaces | X | ✓ | X | X | X |
| Decrease Solar Radiation on Building Surface Protrusions | ✓ | X | X | ✓ | ✓ |
| Maximise Distance Between Elevated Spaces | X | ✓ | X | ✓ | X |
| Maximise Shadow On Selected Elevated Open Spaces | X | ✓ | ✓ | ✓ | ✓ |

**Figure 14:** The experiment setup. This figure illustrates the relationship between genes, fitness objectives, and morphological attributes of the primitive.

in extreme fitness values in both the simulations. The calculation of $\beta$ and $\alpha$ surfaces is conditional to the occurrence of certain events (Figs 9 and 10). Thus, there might be solutions within simulations in which $\beta$ and $\alpha$ are not defined and subsequently fitness objectives associated with them will be null. To prevent null solutions from influencing the simulation, they were assigned unfit fitness objective values (either large or small according to the direction of optimization), thus limiting their impact on the comparative analysis conducted at the end of the experiment. The extreme values for some of the fitness objectives resulted in accumulation of solutions at the bottom of the charts presented in Figs 17 and 18.

Comparing Figs 17 with 18 shows that the introduction of the controlling mechanism to maintain $\beta$ at homeostasis drove the simulation to explore more solutions within the domain of the other fitness objectives (Figs 19 and 20 also confirm this). Figures 19 and 20 represent the repeated fitness values for each fitness objective throughout the simulation run. In the graphs, each dark horizontal line signifies that the value in that location of the domain was chosen repeatedly as a fitness value throughout the simulation. The longer lines illustrate that the respective values were chosen repeatedly. After introducing the controlling mechanism as an extra fitness objective in the endothermic experiment, as it is shown in Fig. 20, the horizontal lines are shortened and expanded on a wider spectrum. Although this may be a minor change, it confirms the efficiency of the controlling mechanism in influencing the simulation.

## 7. Conclusions

Within the context of the rapidly changing environmental and climatic conditions, alongside the exponential population growth experienced (and continues to be experienced) in the 20th and 21st centuries, the ability of the functional and structural advances of human societies to develop urban tissues that can adapt dynamically to these changes is being challenged. To do so, cities must aim to maintain homeostasis of multiple parameters across a range of scales (defined in biology as *controlled variables*) to both actively and dynamically adapt to changes in the immediate (as well as long term) changes in the city's environmental context. More importantly, the adaptation of cities should evolve in response to the city's size and growth rate. As discussed throughout the paper, homeostasis is a critical property in natural species in which it equips them with the ability to adapt and survive in the face of environmental pressures on both the ontogenetic scale and the phylogenetic scale; Torday (2015) prescribes this as a *diachronic* process that is completely independent of scale. As such, incorporating homeostatic principles of natural systems into the morphological design and development of blocks and

**Table 2:** Experiments 1 and 2 were run multiple times, after which the variance, mean value, and hypervolume indicator of the pareto front for each of the three simulations were recorded and compared.

**Experiment 1 (Ectothermic)**

Variance comparison of pareto front

| | Fitness objectives | | | |
|---|---|---|---|---|
| Simulation | 1 | 2 | 3 | 4 |
| Simulation A | 0.000112 | 0.132216 | 0.000386 | 0.000674 |
| Simulation B | 0.00069 | 0.142426 | 0.001586 | 0.000222 |
| Simulation C | 0.000272 | 0.173837 | 0.001388 | 0.000544 |

Mean value comparison of pareto front

| | Fitness objectives | | | |
|---|---|---|---|---|
| Simulation | 1 | 2 | 3 | 4 |
| Simulation A | 0.000125 | 0.775904 | 0.000741 | 0.000938 |
| Simulation B | 0.000378 | 0.74141 | 0.001746 | 0.000651 |
| Simulation C | 0.000268 | 0.817878 | 0.001375 | 0.000882 |

Hypervolume indicator comparison

| Simulation | Hypervolume indicator |
|---|---|
| Simulation A | **0.896468** |
| Simulation B | 0.883478 |
| Simulation C | 0.738701 |

**Experiment 2 (Endothermic)**

Variance comparison of pareto front

| | Fitness objectives | | | | |
|---|---|---|---|---|---|
| Simulation | 1 | 2 | 3 | 4 | 5 |
| Simulation A | 0.00013 | 0.241563 | 0.000759 | 0.000218 | 12.35601 |
| Simulation B | 0.000222 | 0.167121 | 0.000758 | 0.001145 | 7.592146 |
| Simulation C | 0.000228 | 0.158757 | 0.000631 | 0.000321 | 4.167373 |

Mean value comparison of pareto front

| | Fitness objectives | | | | |
|---|---|---|---|---|---|
| Simulation | 1 | 2 | 3 | 4 | 5 |
| Simulation A | 0.000224 | 0.88939 | 0.001164 | 0.000615 | 7.270632 |
| Simulation B | 0.000213 | 0.833184 | 0.000997 | 0.001054 | 5.409405 |
| Simulation C | 0.000261 | 0.817455 | 0.000941 | 0.000619 | 3.807487 |

Hypervolume indicator comparison

| Simulation | Hypervolume indicator |
|---|---|
| Simulation A | **0.916474** |
| Simulation B | 0.910706 |
| Simulation C | 0.832228 |

superblocks in the urban fabric has the potential of yielding an effective modus operandi, one that equips cities approaching their critical threshold with the capability of adapting and responding with greater efficiency to environmental and climatic changes.

The conducted experiments highlighted the understanding and analysis of biological homeostatic principles, and their consequent application within an evolutionary simulation, to generate design solutions that were associated with morphological (and underlying genetic) characteristics that responded to the defined *homeostatic* range coded within the simulation. The analysis and comparison between the endothermic and ectothermic experiments presented the success (and failure) of the simulation in ensuring that the evolved solutions efficiently responded

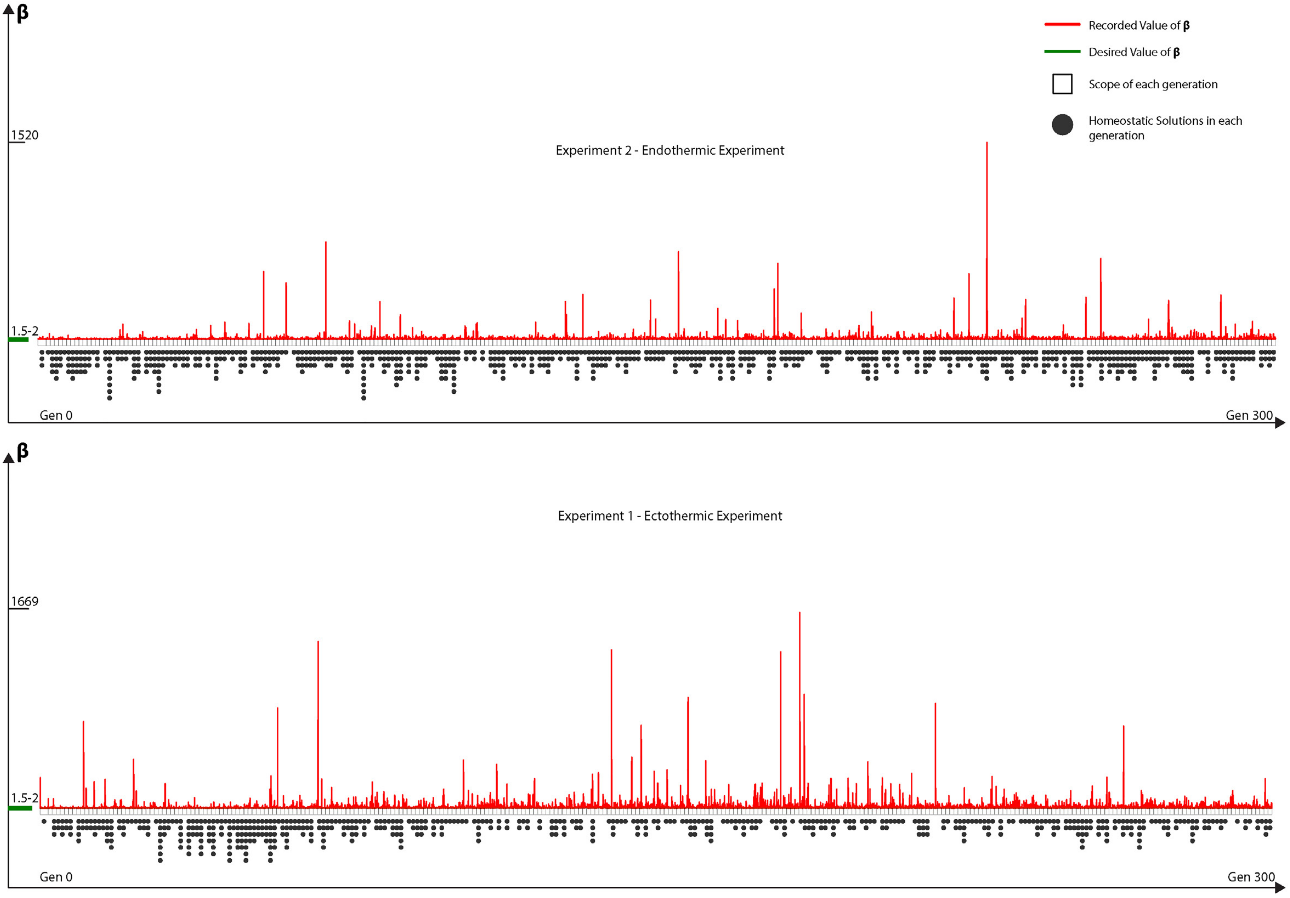
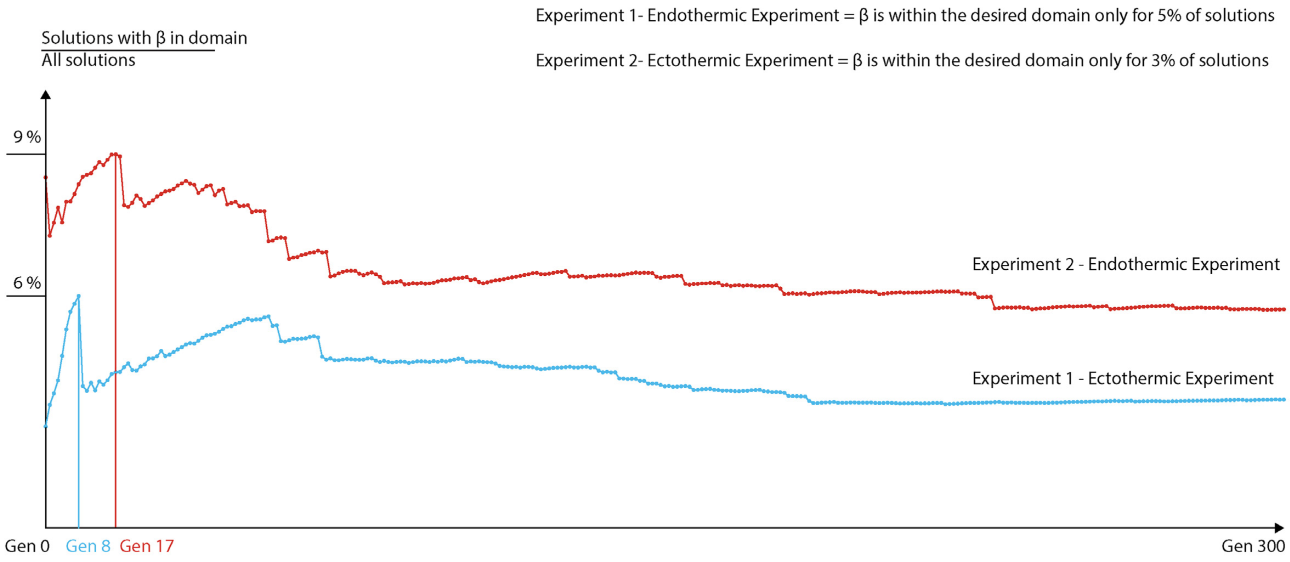


**Figure 15:** Oscillation of the parameter *β* throughout the endothermic and ectothermic simulations.


Experiment 1- Endothermic Experiment = β is within the desired domain only for 5% of solutions

Experiment 2- Ectothermic Experiment = β is within the desired domain only for 3% of solutions

**Figure 16:** Comparison of the overall performance between the endothermic and ectothermic experiments.

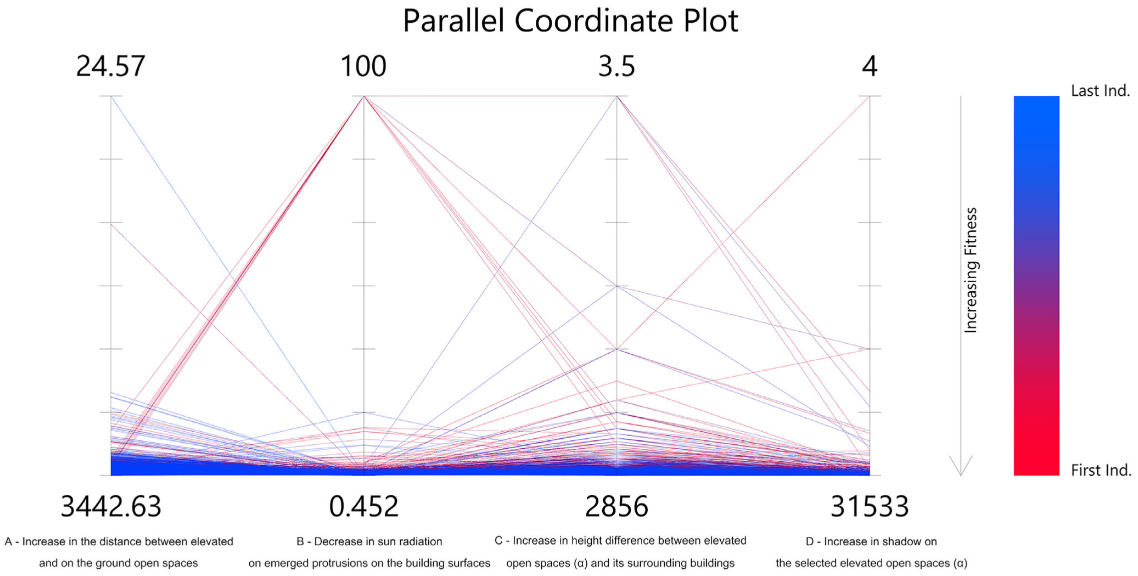


**Figure 17:** Parallel coordinate plot of ectothermic experiment. Comparing the fitness values between the objectives of the ectothermic experiment.

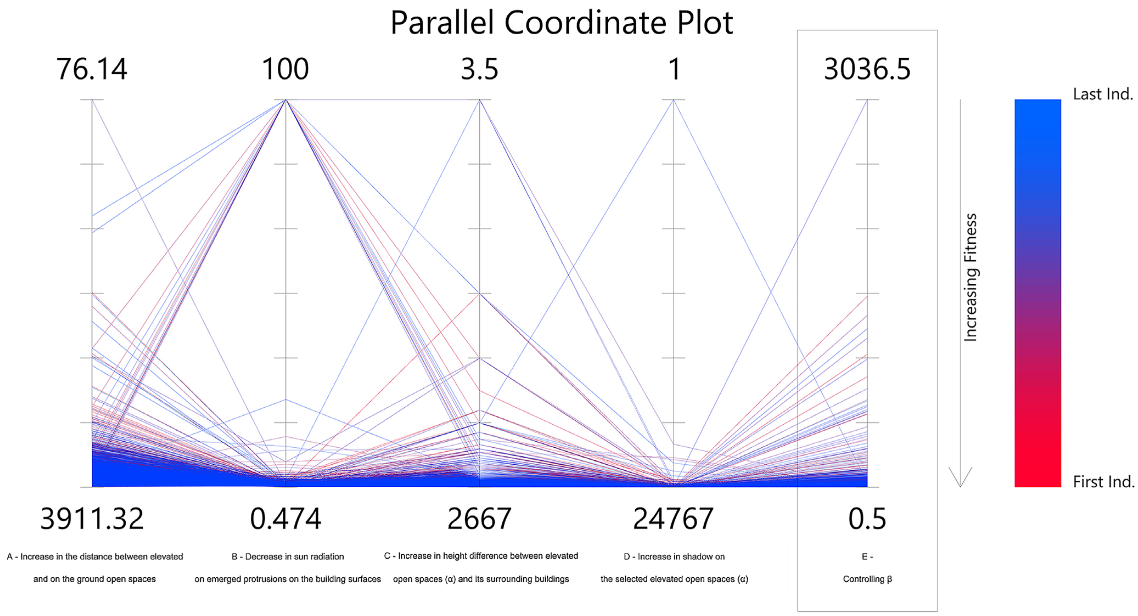


**Figure 18:** Parallel coordinate plot of endothermic experiment. Comparing the fitness values between the objectives of the endothermic experiment. The marked area represents the controlled mechanism that was introduced to the simulation as an extra objective.

to the environmental conditions driving the algorithm. As stated earlier, homeostasis is a process and is not solely defined by the outcome. Figures 15 and 16 illustrate each simulation's process in respect of the maintenance of the value $\beta$ and its subsequent success or failure.

Further analysis must be undertaken to discover to what extent this is an effective mechanism to maintain homeostasis within the urban patch. The authors are currently continuing their research in generating longer simulation runs with refined algorithmic setups in an attempt to recreate the successful results presented herein within a larger simulation. In addition to this, the aim of the experiments presented in this paper was to study the effectiveness of application of a Boolean condition in evolutionary simulations to generate urban morphologies in which an important urban parameter (in this paper $\beta$, a proxy value was set to examine such method) is being maintained in a narrow range (principles driven from endothermic species). However, the increasing intensity and rate of environmental changes in recent years may necessitate to develop urban patches that can be adapted to a wider range of changes. Future work will study the effectiveness of such adaptions, in which the morphological attributes of urban form is responsive to a wider range of environmental changes (through principles driven from ectothermic species).

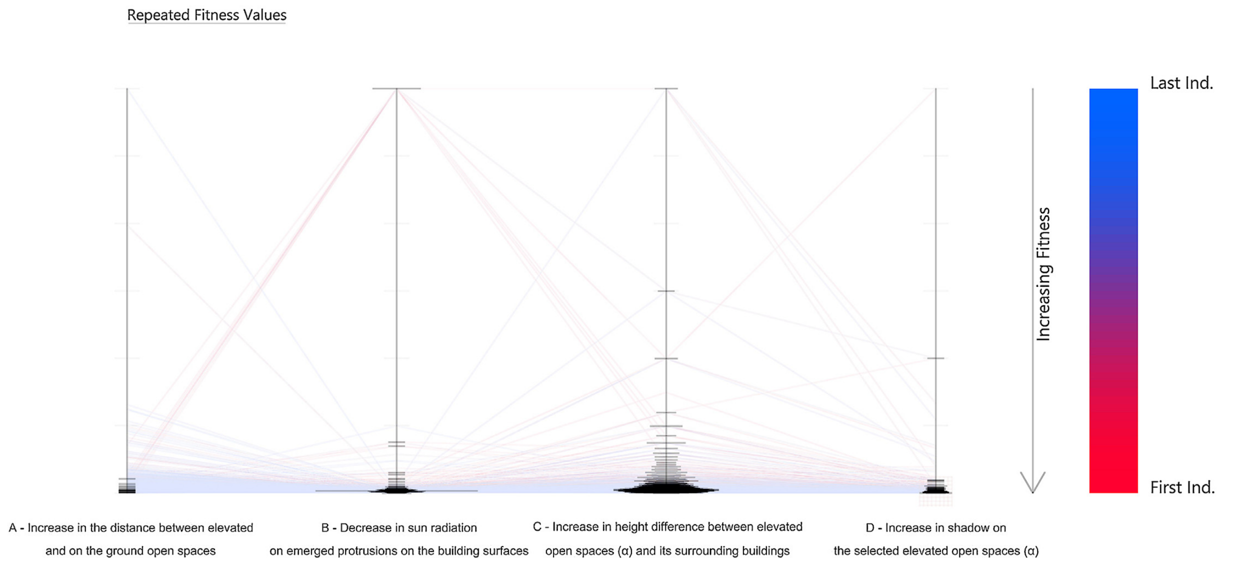


**Figure 19:** Repeated values. The most repeated fitness values for the objectives of the ectothermic experiment.

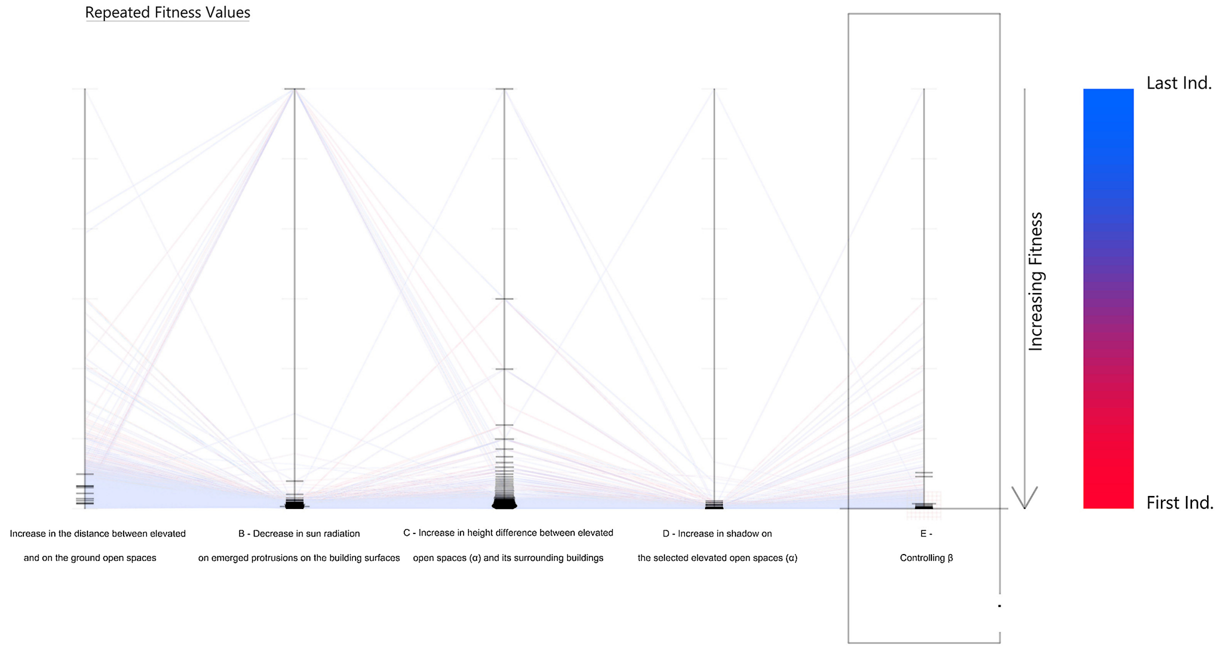


**Figure 20:** Repeated values. The most repeated fitness values for the objectives of the endothermic experiment.

## Conflict of interest statement

Declarations of interest: none.

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