



## Evolutionary Design Processes with Embedded Homeostatic Principles - Adaptation of Architectural Form and Skin to Excessive Solar Radiation

Milad Showkatbakhsh<sup>1</sup> , Saam Kaviani<sup>2</sup>  and Michael Weinstock<sup>3</sup>

<sup>1</sup>Architectural Association (AA) School of Architecture, [Showkatbakhsh@aaschool.ac.uk](mailto:Showkatbakhsh@aaschool.ac.uk)

<sup>2</sup>London South Bank University, [Kavianis@lsbu.ac.uk](mailto:Kavianis@lsbu.ac.uk)

<sup>3</sup>Architectural Association (AA) School of Architecture, [mweinstock@aaschool.ac.uk](mailto:mweinstock@aaschool.ac.uk)

Corresponding author: Milad Showkatbakhsh, [Showkatbakhsh@aaschool.ac.uk](mailto:Showkatbakhsh@aaschool.ac.uk)

**Abstract.** Natural systems develop efficient means of adapting to extreme environmental stresses throughout their evolutionary developments. Homeostasis is the term for the biological processes by which individual beings and collectives maintain their equilibrium in their environment, and there is a wide range of morphological and behavioral traits across multiple species that are rooted in their homeostatic mechanisms throughout their lives. To examine and reflect on the interrelations of forms, processes, and behaviors can yield useful strategies to develop architectural morphologies with significant environmental performance enhancements. An evolutionary design process with embedded homeostatic principles to generate building clusters with morphological characteristics to enhance the clusters' environmental performance in a context with excessive solar radiation has been proposed in this paper.

**Keywords:** Architecture; Computation; Evolution; Biology; Homeostasis; Morphology; Skin; Genetic Algorithm; Computer-Aided Design.

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### 1 INTRODUCTION

Temperature regulating mechanisms of the architectural spaces in regions with excessive solar radiations has always been a challenging task. The European Council reports that buildings currently consume an estimated 40% of the region's energy (predominantly for cooling and heating mechanisms) and are responsible for up to 36% of the European Union's CO<sub>2</sub> emissions [10].

Nature, as a repository of forms and processes, has always been a source of inspiration for solving real-world problems across different disciplines. Evolution is the mechanism by which natural systems have evolved and is compelling to investigate in order to derive a design methodology for problems of adaptation to the environment. According to the biologist, John S. Torday, homeostasis as a scale-free biological process plays an essential role in the adaptation of species to their environment throughout their evolutionary developments [35]. Through understanding the significance of the homeostatic processes of species in their evolutionary developments, a design

process is proposed in this paper that highlights the importance of the morphological properties of buildings in their adaptation to excessive solar radiation.

## 2 THE PROBLEM DEFINITION

Cities are amongst the major consumers of energy globally with a significant effect on CO<sub>2</sub> emissions in recent decades. This results in sudden environmental changes. The existing regulating mechanisms for environmental fluctuations have contributed to the loss of a significant amount of energy through implemented heating and cooling mechanisms [24]. The cooling systems utilize more energy in summer than the heating systems in winter. These systems are being utilized extensively in the countries with excessive solar radiation, e.g. the Persian Gulf region, and lead in extreme electricity loads [3].

There is an escalating need to consider these factors, not only in the later stages of design (i.e. insulation) but in the early stages of design explorations. The European Union funding numerous projects to advance the research in this sector [39] is indicative of the urgency of this problem, and actions need to be taken for both existing and new buildings. In contrary to some of these programs that are committed to constructing retrofitting or setting up energy-efficient technologies, facades, superior insulation resources and greener energy supplies [32]—experiments presented in this paper highlight the significance of early design explorations in addressing these issues by providing a novel methodology to implement the core principles of homeostasis in the evolutionary design processes to evolve adaptive architectural forms and skins.

Additionally, the proposed design system provides a novel selection strategy that gives designers necessary insight and knowledge to interrogate the generated results of an evolutionary algorithm based on their objective and subjective preferences. This paper presents a design methodology to address the rising issues of increased energy consumptions in the areas with extreme solar radiation that are intended to neutralize the impacts of extreme hot climates. In contrary, the presented design system presented provided a streamlined generative workflow to factor such issues from the early phases of design explorations.

## 3 NATURAL SYSTEMS

The seminal 19th-century texts of Bateson have been profoundly influential in the development of the biological science of evolutionary development. Bateson wrote the first substantial account of variation in living forms [6]. His argument rests on his analysis of the morphology of living beings, observing that, “the bodies of living things are mostly made up of repeated parts” [6], organized bilaterally or radially in series. Many body parts themselves are also made up of repeated units so that morphological changes or variations occur by modifications to the arrangement, number or order of parts. There is something here that speaks directly to the principle of adaptation to a changing environment in which living beings exist. Adaptive changes are not only context-dependent but are a continuous process of mutation that occurs over multiple generations. Adaptation is an evolutionary response to gain a metabolic advantage and is produced through mutation and natural selection.

Metabolic processes are actuated by the exchange of energy and material between species and their local environment [11]. Species have evolved morphological characteristics, responsive behaviors and processes that help to sustain the exchange of matter and energy with their environment. These exchanges are monitored and maintained through responsive regulatory mechanisms. Homeostasis (the term coined initially by Cannon [4]) is a responsive process by which the organism can sustain a steady state through internal and external changes. This process comprises sensing, decision-making and reactions that are widely distributed in the skin and the internal organs.

J. Scott Turner highlights that homeostasis is not the final result; instead, an independent process triggered by un-favorable internal or external changes [36]. J. S. Torday further emphasizes

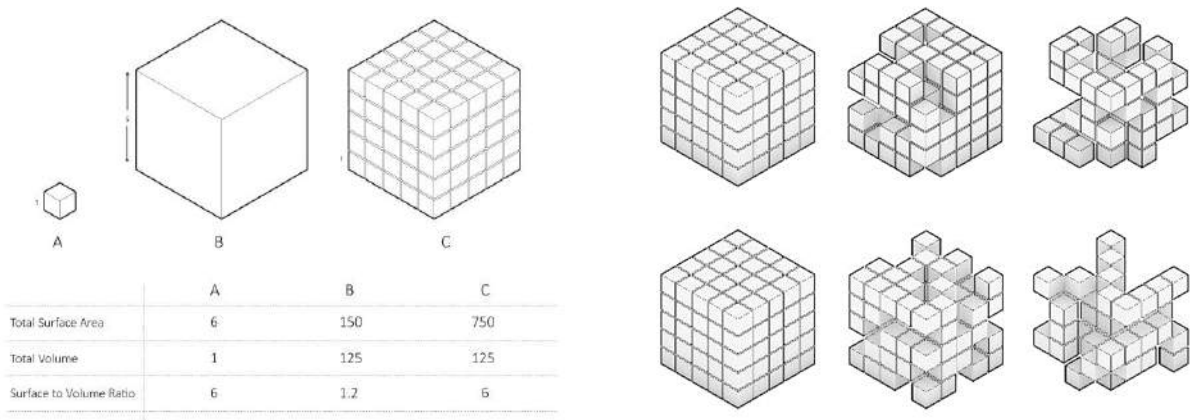
the significance of such processes in the evolutionary development of species. It ensures their adaptation to the ever-changing environmental conditions by providing a “reference point for change” [35]. This ‘scale-free’ process [35] by which all biological systems maintain their vital parameters in an acceptable range has been manifested physically through their morphological characteristics throughout their evolutionary developments.

**3.1 Homeostasis and Morphology**

Gerlee et al. state that the ‘self-regulatory’ aspect of homeostatic processes in response to the changes will affect the final form and function of a system [14]. Homeostasis occurs at multiple levels within organisms and controls a wide range of parameters, one of which is heat. Thermoregulation is the primary process by which exchange of heat between a system and its immediate environment is regulated. This exchange occurs through three mediums: radiation, convection, conduction. Solar radiation is the only medium that will be studied in this paper.

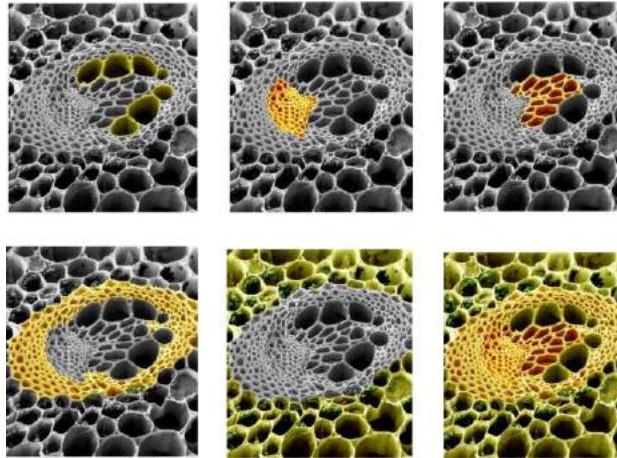
The objective of any homeostatic process (e.g. thermoregulation) is to cancel the effects of an un-favorable stimulus to the system. These processes comprise three main elements: 1. A setpoint, 2. Receptors 3. Effectors [28]. Effectors will adjust the system back to its set point through responsive feedback loops should the receptors detect any deviation. It is this balance that allows the organisms to adapt and survive in the fluctuations in their environment efficiently and causes morphological attributes to emerge. These characteristics are manifested across a range of scales, including the skin. The biological and physical characteristics of the skin play an enormous role in protecting the body from ecological stresses such as solar radiations [9].

The skin of the living species contributes to the control of heat fluxes significantly. The ratio of the skin surface area to the volume of the whole affects the heat dissipation and preservation significantly. Having a higher surface to volume ratio creates more surface area for heat to be dissipated (suitable for hot environmental conditions). On the other hand, a lower ratio limits the surface area for heat dissipation and leads to heat preservations (ideal for cold environmental conditions). The skin’s morphological characteristics can create pockets of shadow on the overall form. This will create a self-shading mechanism on the overall form, which assist the heat dissipation. (Figure 1).



**Figure 1:** The left image shows how total surface area of a form increases dramatically by increasing the internal cells while keeping the volume the same. This is the morphological approach that is implemented in the experiments presented in this paper to increase the surface area to volume ratio. The right image shows self-shading that causes the reduction of heat gain. Thereby reduces the overall temperature of the form exposed to direct sunlight. This is the morphological approach that is implemented in the experiments presented in this paper to increase the self-shading mechanism.

These morphological characteristics vary in scale, from macro to microscale. The arrangement, grouping and formal attributes of the cells in the stem of most plants have evolved to improve structural capacity and strength, enabling the transportation of materials [1], which plays a significant role in maintaining metabolism and homeostasis (Figure 2)[30].



**Figure 2:** The transverse section of a young root of a buttercup illustrates different cell grouping. This is the morphological approach that was utilized in the formulation of skin. As shown in this figure, the stem is made up of specialized cells and differentiated vessels which are arranged as closely packed bundles. This morphological arrangement asserts improved structural capacity, increased strength, and improved flexibility which is a great inspiration for this research in terms of generating architectural skins with grouped cells for different functionality.

### 3.2 Relevance in Design

The skin, which is inseparable from the overall morphology of an organism is a crucial element in controlling the exchange of energy and matter between inside and outside environment. Architectural forms and skins in a similar fashion are situated between internal environments where human activities occur and the external environment. As in biology, it is crucial that the border between the inside and outside contains mechanisms for the exchange of matter and energy if necessary. These exchanges are enabled by processes and unique morphological characteristics. Architectural forms and skins can be evolved to obtain morphological characteristics suitable for their environments.

As noted in the differences between the revised and the original editions of Steadman, 1979, 'The Evolution of Designs', the application of principles of natural systems and processes can play a pivotal role in driving the architecture in closer conformity to the environment [33]. Evolutionary design processes have been used as robust problem-solving strategies in architecture and design disciplines in recent years. Given the importance of the homeostatic behaviours of species in their evolutionary development [35], the application of these regulatory methods as feedback mechanisms in the evolutionary design processes is investigated in this paper. More precisely, heat and thermoregulation are the points of interest in this context.

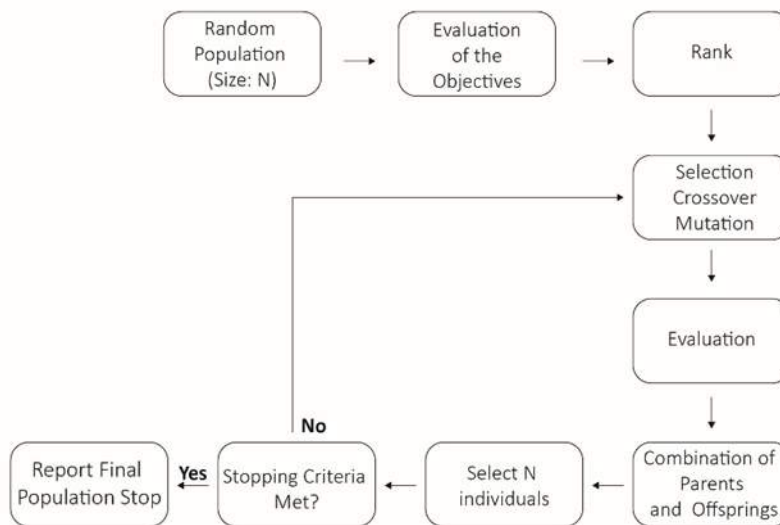
In contemporary practice cooling and heating mechanisms use up to 60% of the entire energy in the buildings [25]. Given the significance of the morphological characteristics of species in their adaptation to the extreme environmental conditions, this paper investigates architectural forms and skins produced by an evolutionary design system within which the morphology of the building cluster is contributing to their adaptation to the contexts with excessive solar radiation. For this study, the

Al-Bahr towers have been selected as case studies. Next section presents a brief history of the application of evolutionary optimization techniques at the early stages of design.

#### 4 COMPUTATIONAL PLATFORM

Evolutionary multi-objective optimization strategies have been utilized widely since the late 20th century as problem-solving methods. The work of Sewall Wright in the 1930s is the earliest instance of the application of evolutionary principles as optimization processes [37]. Midway through the 20th century, John Holland's genetic algorithms (GA) [15], Rechenberg and Schwefel's evolutionary strategies (ES) [27] and Fogel et al.'s evolutionary programming (EP) [13] were developed independently from one another and led to the establishment of a unified field of evolutionary computation in the late 20th century [7].

Erns Mayr described the evolutionary model as a two-step process; random variation within the genome (instructions behind building the geometry in this context) of a phenotype (geometry), and subsequently the selection of the phenotype through environmental pressures [22]. Most of the widely used evolutionary algorithms such as NSGA-II [8] have been developed based on Mayr's definition. The algorithm goes through a primary loop and starts by generating an initial random population of solutions. It continues with modifications of genomes through random variations and evaluation of the solutions on their objective performance. It ends by selecting a group of solutions based on a predefined selection mechanism [12] (Figure 3).



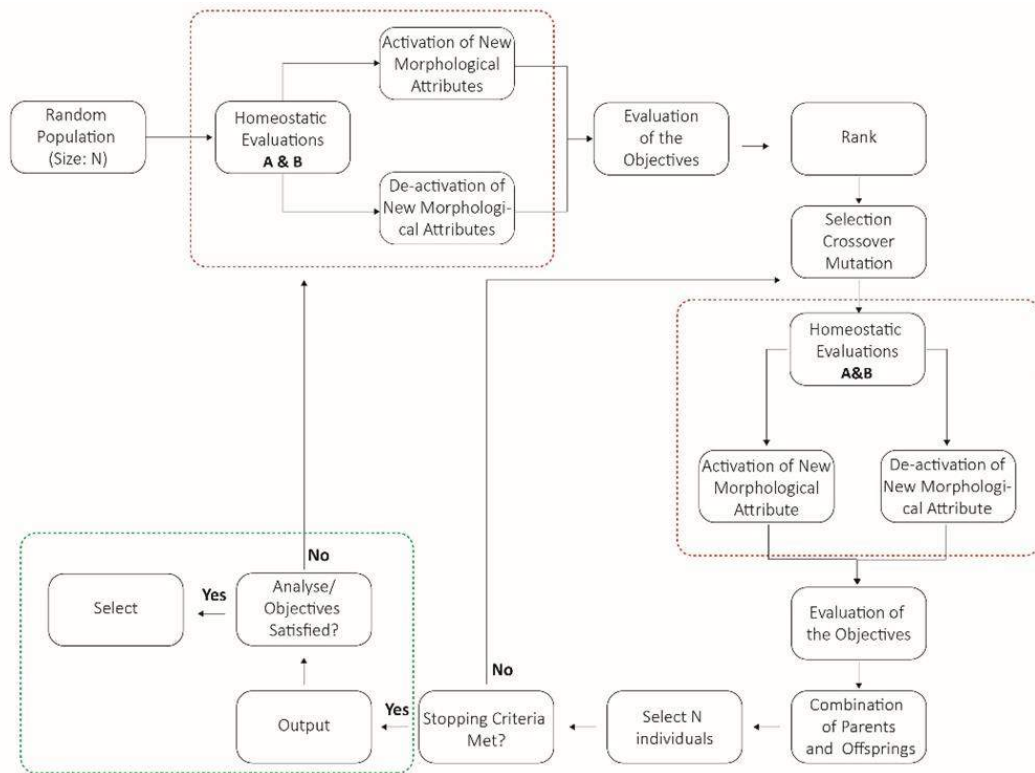
**Figure 3:** NSAGII algorithm pseudocode.

In recent years, evolutionary optimization processes have gained recognition in architecture and design disciplines, both in academia and practice. Research conducted by Ayman Hassaan et al. investigated the use of evolutionary optimization in the design phase by exploring geometric formations of the skin at the early stages of design [18]. Yun Kyu Yi implemented NSGA 2 algorithm in his investigations of optimizing building facades [38]. Machairas et al. used the genetic algorithm to address a set of conflicting objectives in the early design phase of a building [17]. Bionic Partition, a partition that was designed by The Living Office in collaboration with Airbus and Autodesk is an example of the application of evolutionary optimization techniques in practice with functional and structural objectives [34].



Due to the nature of homeostatic processes, the application of homeostatic principles in the design processes requires an iterative generative model that includes a mechanism of assessment and reconfiguration of the generated results. Thus, the experiment presented in this paper utilizes evolutionary computation as the main framework through which generated design solutions address the predefined environmental pressures via an increase in their fitness [16].

In this context, heat received by solar radiation is the parameter for which the homeostatic mechanism will be investigated by inserting the secondary evaluation mechanisms into the evolutionary simulation (Figure 4). With a similar objective but a different algorithmic approach to the experiments presented in the paper [31] (respectively feedback loops vs Boolean conditions), the experiment in this paper investigates to what extent the application of homeostatic feedback mechanisms in the evolutionary simulations will be efficient to generate adaptive forms.



**Figure 4:** The modified evolutionary simulation workflow with two secondary evaluation mechanisms. The red squares show the modified stages. The green square shows the added step on the application of evolutionary simulation in design using Wallacei.

The main components of a homeostatic process (setpoint, receptor and effector) are mapped to a set of algorithmic conditional statements within the main design problem algorithm. Building upon Torday's statement of 'a reference point for change', these algorithmic conditional statements as the secondary evaluation mechanisms create the reference points for morphological changes through the evolutionary simulation.

The presented experiment utilizes multi-objective Non-Dominated Sorting Genetic Algorithm II (NSGAI) developed by Deb. et al. [8] as the base algorithm based on which the evolutionary simulation is developed. Rhinoceros3D, Grasshopper3D and its plugin 'Wallacei' [19] are used to run the simulation and analyze the results thoroughly. The algorithm parameters within the evolutionary

simulation were set to the following values (Table 1). (for a detailed description of the terminology used in the simulation, please see [21] [20]).

<i>Table</i>	<i>Short Description</i>	<i>Amount</i>
Generation Size	Number of individuals per generation	25
Generation Count	Number of generations in the simulation	300
Crossover Probability	Percentage of solutions that reproduce in each generation	0.9
Mutation Probability	Percentage of mutation $1/$ (number of variables)	$1/n$
Crossover distribution index	Probability of similarity of the offspring to the parents	20
Mutation Distribution Index	Probability of similarity of the offspring to the parents	20
Random Seed	Random seed in the simulation	1

**Table 1:** Simulation parameters.

## 5 CASE STUDY

One of the regions with increasing interest in construction while having extreme ecological conditions in summers is the Persian Gulf. The temperature of this region can rise to 60 °C in summers [26]. The Al Bahr project, located in Abu Dhabi's financial center, comprises two identical 145 m tall towers with 26 stories each. The Al-Bahr Towers are amongst many other buildings to employ methods of neutralizing the effects of extreme temperature rise in the region [2]. The skin system has external kinetic panels to reduce the effects of excessive solar radiation exposure to the buildings [2] (Figure 5).



**Figure 5:** The left image, Al-Bahr Towers. The right image is the view from inside to outside of Al-Bahr Towers.

The implemented skin system in the Al-Bahr project is the reason for choosing this project as the case study. Based on the results of surveys that were conducted by [3], on the evaluation of adaptive facades, 60% of the users are uncomfortable with the natural light that is received through the skin. The use of kinetic panels is a response to the problem that was created initially by the application of glass material to maintain the freedom of view from inside to outside in the desert environment. The mechanical movements of the skin have made it responsive to the external conditions; however, on the other hand, this increases the cost of energy consumed by this system and subsequently, its maintenance expenditures. The skin also tremendously increased the cost of construction to 390

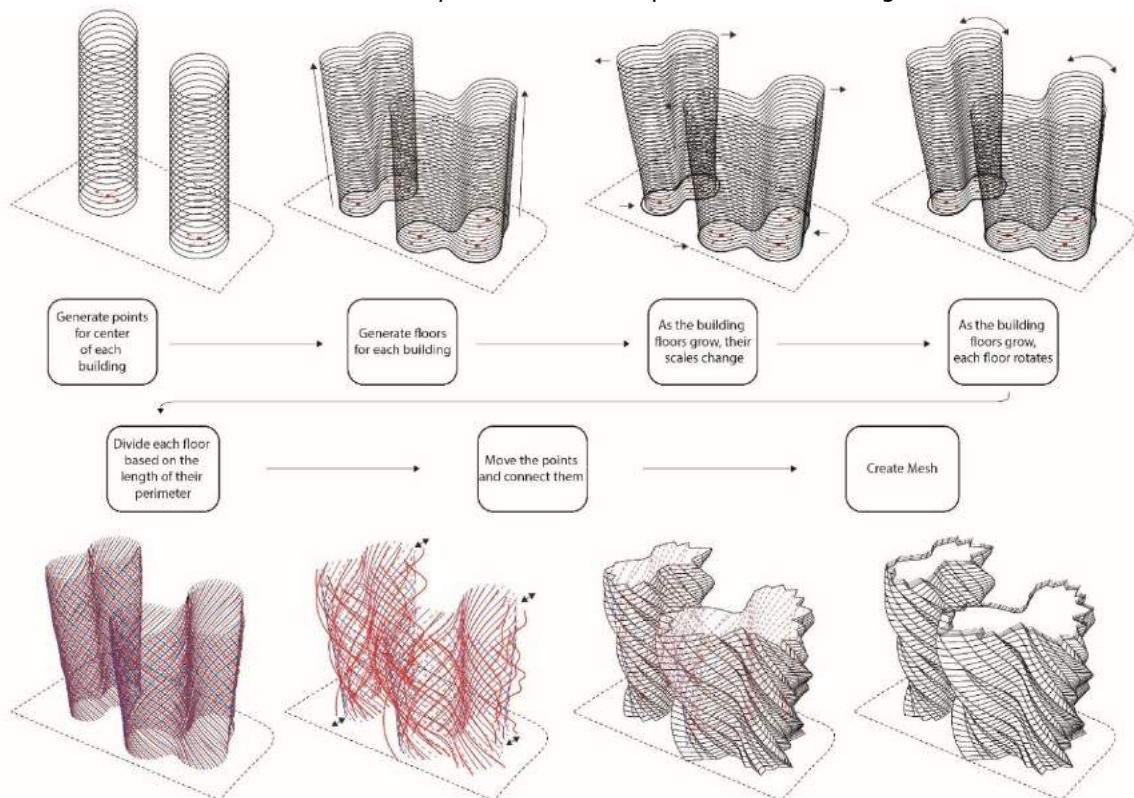
million Euro [3]. Given the uniqueness of the skin system in this project, the overall morphology of the towers comprises two cylinders with no formal attributes suitable for the exposed excessive solar radiation. The complexity of the skin and the simplicity of the morphology of the Al-Bahr Towers were the reasons to investigate the skin to morphology relationship in this paper.

Conventional cooling and heating mechanisms use up to 60% of the entire energy in buildings [25]. By choosing the Al-Bahr Towers as case studies, the significance of the buildings' morphological characteristics together with their skin formation in adaptation to the hot environment is examined. The objective is to address a possible contribution of the principles of thermoregulatory processes (and their morphological manifestations in biology) in evolving an environmentally conscious cluster of buildings.

## 6 EXPERIMENT SETUP

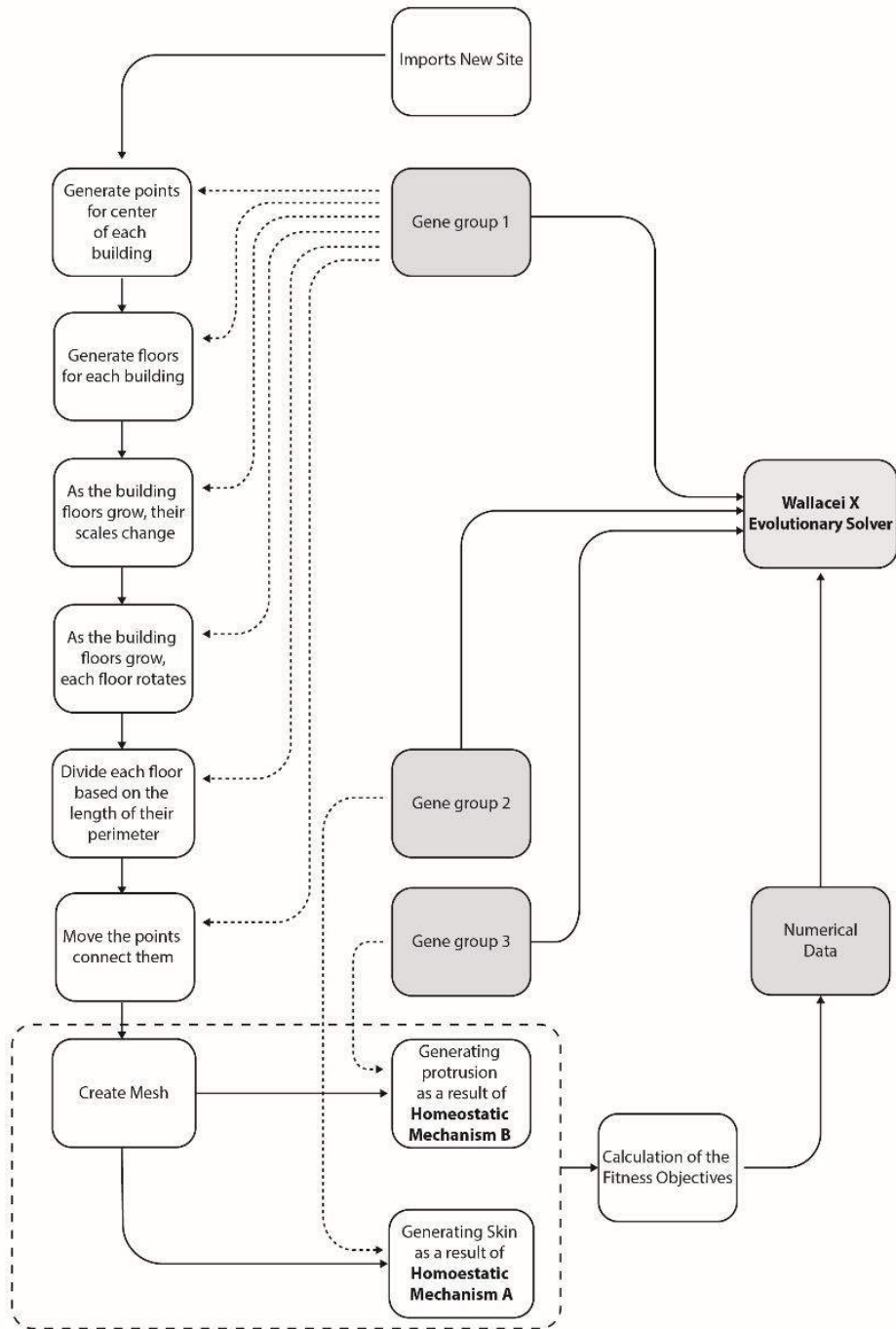
In the context of this paper, the summer solstice (June 21) is considered the date based on which solar radiation is calculated and studied. Solar radiation is the only way by which heat can be exchanged. Therefore, the primary aspect of the experiment is examining the significance of the morphology and skin in adaptation to excessive solar radiation. The overall form and skin will be generated through evolutionary simulation with homeostatic feedback mechanisms. The selected group of generated solutions will be compared to the Al-Bahr Towers.

Utilizing the form of the Al-Bahr Towers as the underlying geometry component, a primitive geometry was constructed algorithmically to enable the changes necessary in the simulation (Figure 6). Multiple sets of genes have been added to the genome to allow the modifications should simulation favour them. The evolutionary simulation set up is illustrated in Figure 7.



**Figure 6:** The algorithmic construction of the primitive geometry based on Al-Bahr towers geometry.





**Figure 7:** The pseudocode of the design problem onto which the evolutionary simulation will be operating. Figure 6 shows the geometrical representation of each step and tables 2,3 and 4 illustrate the gene groups and their domains.

Gene group 1, 2 and 3 respectively control the construction of the base primitive, morphological attributes of homeostatic mechanism A and B. Gene group 1, 2 and 3 respectively control the construction of the base primitive, morphological attributes of homeostatic mechanism A and B (explained in the following section) (Figures 7, Table 2, Table 3, Table 4). In total, the number of genes in the simulation is 1835, giving the simulation freedom of choosing among 294385 unique values as the input data to generate the geometries. Accordingly, the size of the search space is calculated as below.

$$\text{Size of the Search Space} = 1.25 \times 10^{3308}$$

The statistical analysis of the simulation will be conducted to highlight any emergent patterns in the generative process. Subsequently, a set of candidate solutions will be selected based on a set of defined measurement criteria (explained in the later section). Finally, based on the outlined post-evaluation criteria, the solar radiation exposed to the selected solutions will be compared to the Al-Bahr Towers. The design system elaborates a comprehensive generative workflow that gives designers necessary insight and knowledge to implement evolutionary principles in a design process, evaluate and select the results.

<i>Gene Group 1 (160 Genes) – Base Primitive Instruction</i>			
<i>Subgroup</i>	<i>No. of Genes</i>	<i>Numerical Domain</i>	<i>Function</i>
1	5	20.00 to 40.00	Number of floors
2	5	0.00 to 15.00	Rotation of the floorplates
3	5	1.00 to 1.10	Scalar transformation of floorplates
4	5	0.90 to 1.00	Scalar transformation of floorplates
5	5	50.00 to 200.00	Merging the footprints of the buildings
6	10	0.00 to 1.00	Location of the buildings
7	125	0.75 to 1.25	Creating a self-shading mechanism

**Table 2:** Gene group 1.

<i>Gene Group 2 (175 Genes) – morphological attributes of the homeostatic mechanism A</i>			
<i>Subgroup</i>	<i>No. of Genes</i>	<i>Numerical Domain</i>	<i>Function</i>
1	25	0.10 to 0.50	The offset of the frame of the skin cells
2,3,4,5,6	5 X 30	0.00 to 0.50	Extrusion of the corners of the skin cells

**Table 3:** Gene group 2.

<i>Gene Group 3 (1500 Genes) – morphological attributes of the homeostatic mechanism B</i>			
<i>Subgroup</i>	<i>No. of Genes</i>	<i>Numerical Domain</i>	<i>Function</i>
1,2,3,4,5	5 X 100	0 to 100	Secondary self-shading mechanism location
6,7,8,9,10	5 X 100	0 to 10	Secondary self-shading mechanism length
11,12,13,14,15	5 X 100	0.20 to 3.00	Secondary self-shading mechanism extrusion

**Table 4:** Gene group 3.

### 6.1 Homeostatic Feedback Mechanism

Two secondary feedback mechanisms are added to the evolutionary simulation to steer it towards generating an extra set of formal attributes within the phenotypes. They are called homeostatic mechanism A and homeostatic mechanism B.

Homeostatic Mechanism A (**H-M-A**) directs the simulation to generate the skin system on the buildings should a specific condition be met. Its three main elements can be identified as follows: (Figure 8, Figure 9 and Figure 10) (Table 5).

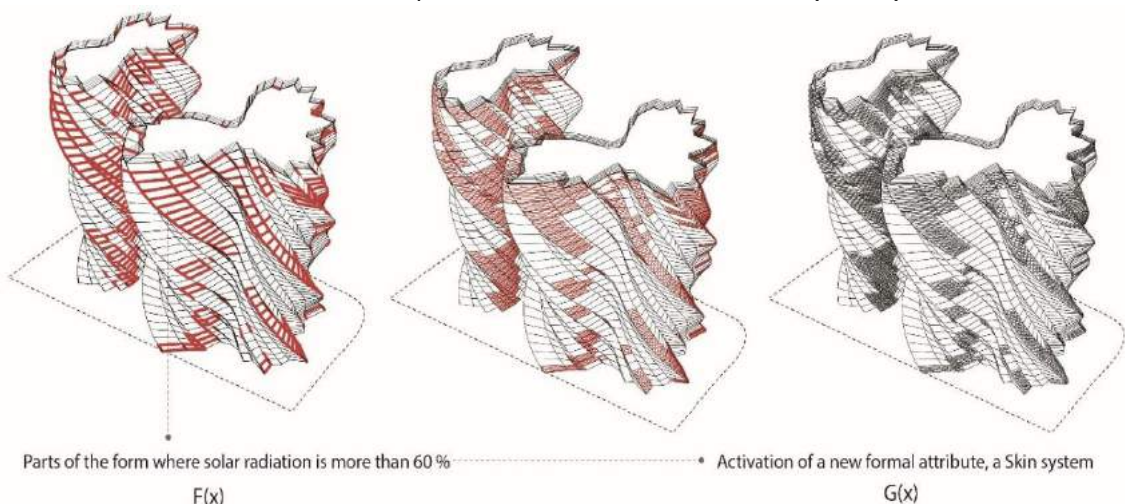
- **Setpoint:** 60% of solar radiation exposure on the building’s form is the threshold after which a responsive feedback mechanism will be activated in order to counteract the deviation (the authors chose the figure 60% as a design input; this number can be modified accordingly in other scenarios).
- **Receptor:** Building forms have been created algorithmically, allowing for the evaluation of the solar radiation on the building surfaces.
- **Effector:** If the amount of solar radiation exceeds 60%, a new morphological attribute will be activated on the exposed surfaces.

```

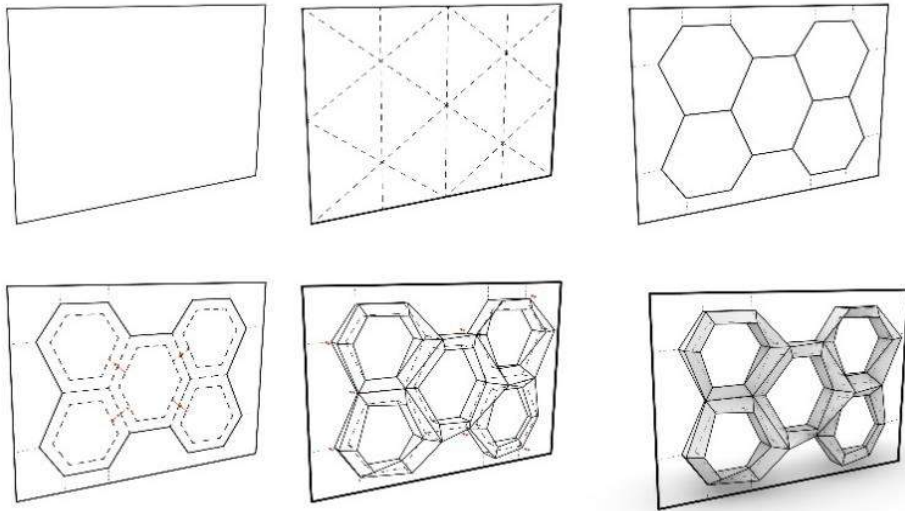
if(F(X) != null)
    G(X);
else
    X;
    
```

<i>Functions and Variables</i>	<i>Description</i>
X	The generated phenotype in each iteration
F ( )	Receptor. The function that returns the parts of the phenotype that receive solar radiation more than 60%
G ( )	Effector. The Function that applies the morphological changes onto the phenotype

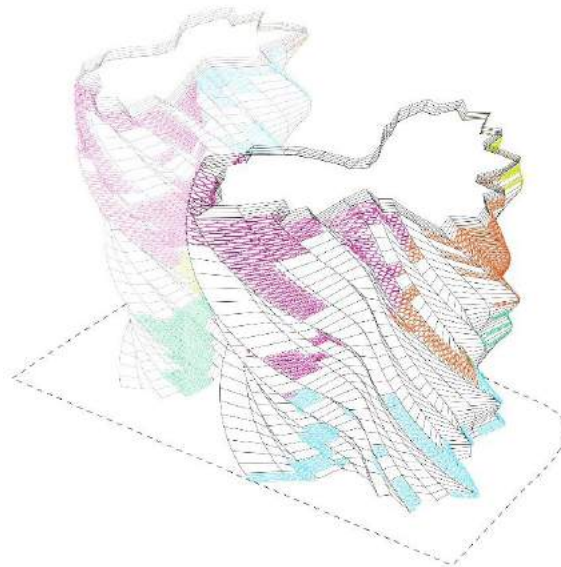
**Table 5:** Description of conditional statement 1 (above).



**Figure 8:** Illustration of H-M-A process and effects (skin system).



**Figure 9:** Illustration of the algorithmic setup of the skin system.



**Figure 10:** The skin system comprises five different cell groups (inspired by figure 2). Each group can be modified and altered by the simulation independently.

The effectiveness of the skin in blocking the excessive solar radiation as well as providing an adequate view to outside relies on the elements that are considered the variables of the morphology of the building skin. These variables are the number of modules, offset size, extrusion size.

By recognising the fixed and variable parameters of the skin in the early design exploration stage, its morphological adaptability can be evaluated to ensure the evolved skin, can be applied to any complex form. The process of setting up the variables and development is illustrated in Figure 9. In this experiment, the n-gon shapes are chosen as the skin system as an example to show that even complex geometries can take advantage of homeostatic principles. Based on the studies derived from the geranium stem cell morphology in the section natural systems, the n-gons (hexagons in this study) enable the cell grouping mechanism for the adaptation to the external stimuli (solar radiation in this research) via different behavioural mechanisms (Figure 10). Additionally, High ratio of surface area to perimeter of n-gons facilitates creating sufficient view from inside to outside while increasing the surface area to volume ratio [23].

Homeostatic Mechanism B (**H-M-B**) affects areas of the buildings with no skin system. Its three main elements are as follows (Figure 11) (Table 6):

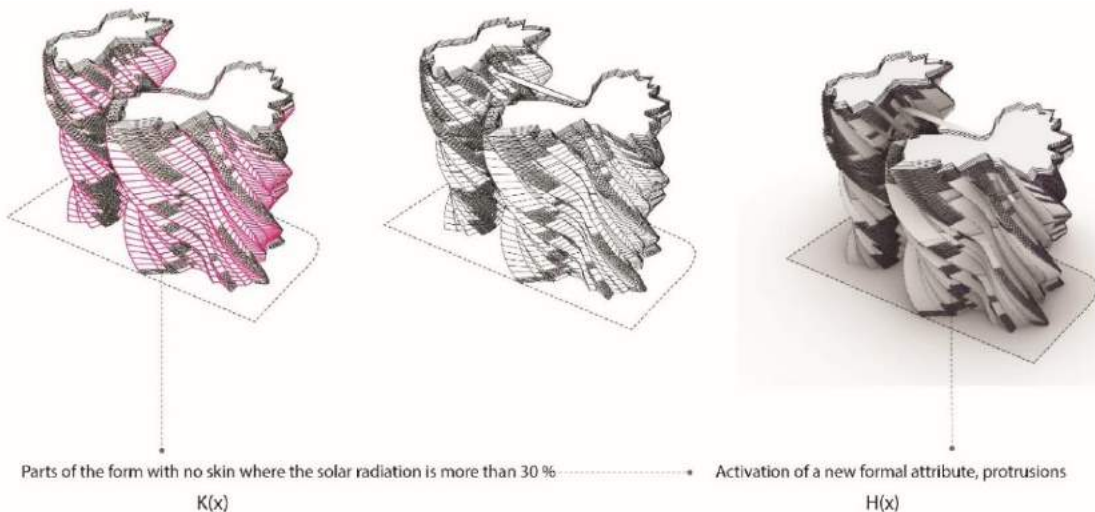
- **Setpoint:** 30% of the solar radiation on the building surfaces with no skin system is the threshold after which a responsive feedback mechanism will be activated in order to counteract the deviation (30% is a design decision by the authors; this number can be modified accordingly in other scenarios).
- **Receptor:** Building forms have been created algorithmically, allowing for the evaluation of the solar radiation on the building surfaces.
- **Effector:** If the amount of solar radiation exceeds 30%, a new morphological attribute will be activated on the exposed building surfaces (protrusions).

```

if(F(X) != null)
{
    if(K(G(X)) != null)
        H(G(X));
    else
        G(X);
}
else
{
    if (K(X) != null)
        H(X);
    else
        X;
}
    
```

<i>Functions and Variables</i>	<i>Description</i>
X	The generated phenotype in each iteration
K ()	Receptor. The function that returns the parts of the phenotype with no skin that receive solar radiation more than 30%
H ()	Effector. The function that applies the morphological changes onto the phenotype

**Table 6:** Description of conditional statement 2 (above).



**Figure 11:** Illustration of the algorithmic setup of the skin system.



## 6.2 Selection of the Fitness

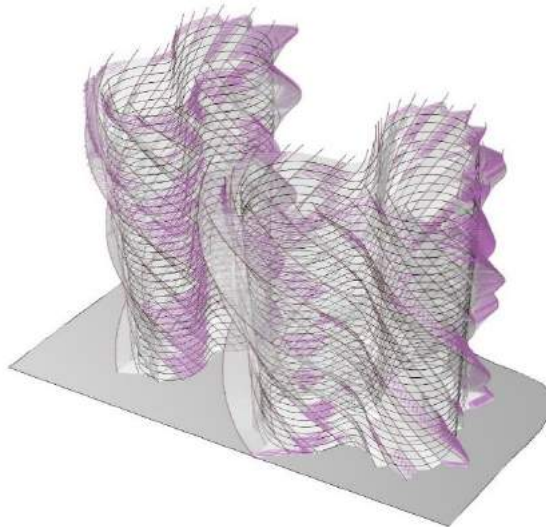
The evolutionary simulation was developed to generate a building cluster in Abu-Dhabi, in the same location of Al-Bahr towers, to optimize the following fitness objectives:

- FO1: To keep the gross floor area (GFA) of the generated solutions as close as possible to the case study (Figure 12).
- FO2: To increase the shadow on the buildings by self-shading mechanisms (Figure 13).
- FO3: To increase the shadow on the ground (Figure 14).
- FO4: To increase the view from inside of the buildings towards the outside (Figure 15).

Each of these objectives was formulated to direct the evolutionary simulation towards the emergence of morphological attributes suitable for the context. Secondary homeostatic mechanisms in the simulation will steer the simulation towards preferred morphological traits by creating reference points for change. However, the architectural application of these fitness objectives holds an equal significance, and they are as follows:

By introducing the constrain on GFA, simulation is trying to optimize for a building cluster, independent from the number of buildings, to generate solutions with GFA as close as possible to the case studies. It ensures the size of the generated solutions is similar to the case studies to conduct a meaningful compression. Wallacei X always tends to minimize the inputted objectives; thus, to keep the GFA constant, this objective is defined as below. By decreasing the value of FO1, simulation ensures the GFA of the solutions is as close as possible to the Al-Bahr Towers (Equation1).

$$FO1 = \left| Area_{Al-Bahr\ Towers} - \sum_{n=0}^n Area_n \right|$$

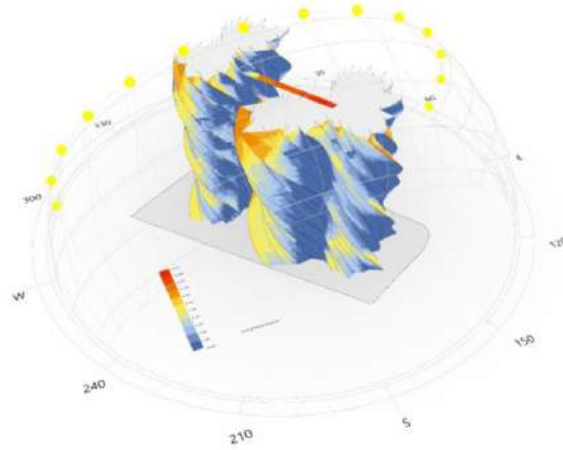


**Figure 12:** Fitness objective 1.

By increasing the self-shading of the building cluster, the morphology will play an essential role in obstructing the solar radiation on itself. It subsequently will contribute to the reduction of the energy required for cooling mechanisms in hot conditions. The geometries are populated by the sample points (Pa). The number of (Pa) is proportional to the volume of the phenotypes. Some sample points are accessible by the sun vectors, and some are blocked (Ps). To increase the self-shading on the buildings, objective two is calculated to increase the number of Ps in the simulation. Since each

solution may have a different number of sample points ( $P_a$ ), (due to their different volumes), the ratio is calculated as the objective (Equations 2).

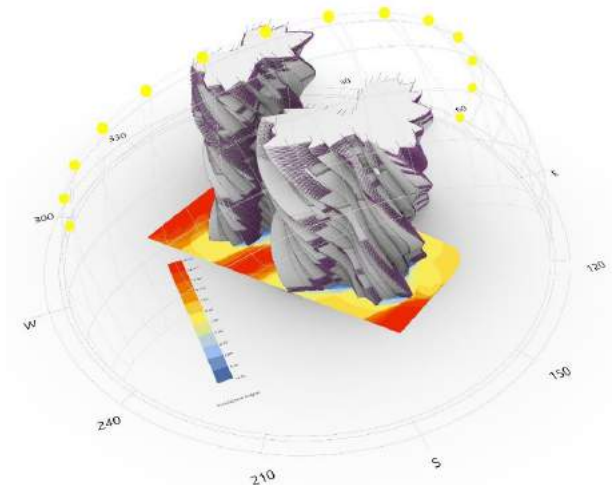
$$\delta = \sum_{n=0}^n P_{an} \quad \theta = \sum_{n=0}^n P_{sn} \quad FO2 = \left( \frac{\delta}{\theta} \right)$$



**Figure 13:** Fitness objective 2.

By increasing the shadow on the ground, spaces on the ground level with pockets of shadow suitable for outdoor activities will emerge. This is an attribute that is missing in the case studies. Fitness objective three is calculated similarly to the fitness objective two, but with sample points which are populated on the ground (PG) (Equations 3).

$$\mu = \sum_{n=0}^n PG_{an} \quad \omega = \sum_{n=0}^n PG_{sn} \quad FO3 = \left( \frac{\mu}{\omega} \right)$$

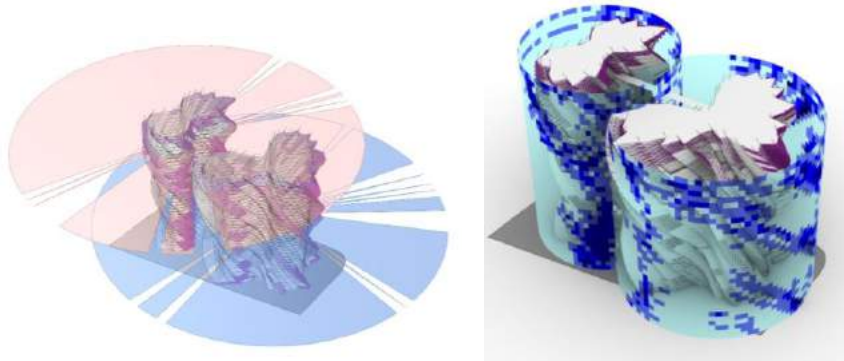


**Figure 14:** Fitness objective 3.

As a result of the inserted homeostatic mechanisms in the evolutionary system, a new morphological attribute (skin system), will be activated. To address the concern regarding the blockage of the view

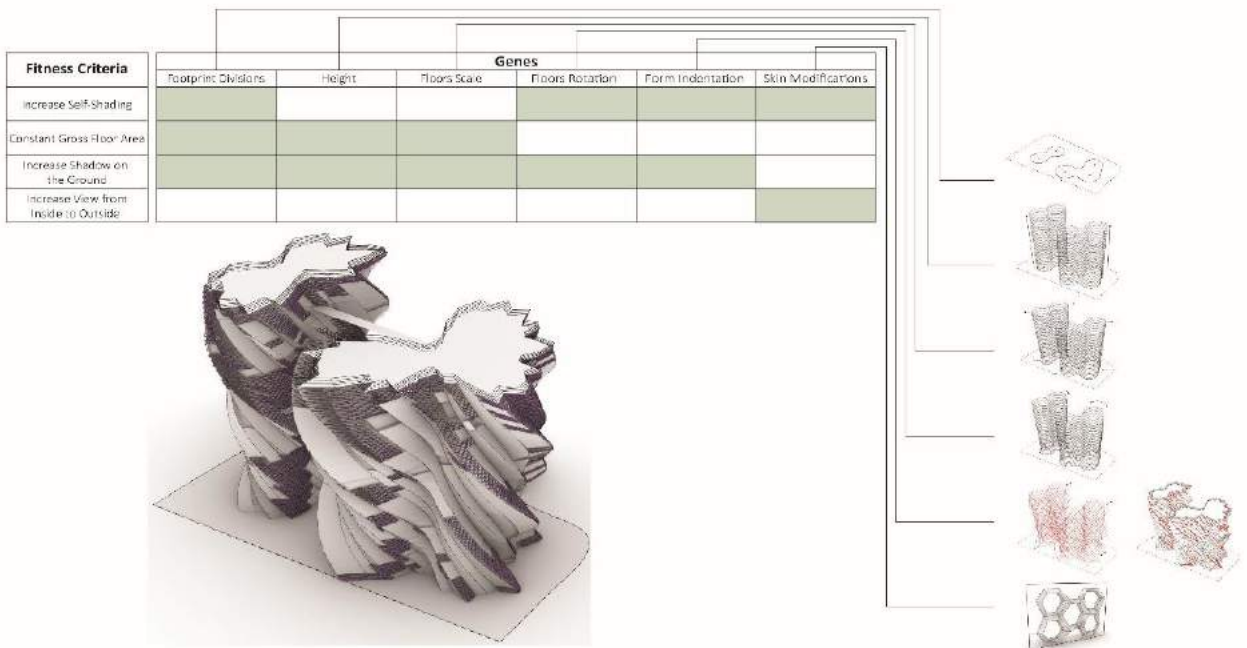
from inside of the buildings towards outside, the fourth objective is introduced to the evolutionary simulation to increase the view from inside to outside. From the centre point of each floor in each building, vectors (Va) are drawn outwards spherically. The skin system will block some of them while some vectors will not hit the skin and pass-through (Vp). Fitness objective four is assigned to increase the number of vectors (Vp) from inside to outside (Equation 4).

$$\alpha = \sum_{n=0}^n V_{an} \quad \beta = \sum_{n=0}^n V_{pn} \quad FO4 = \left(\frac{\alpha}{\beta}\right)$$



**Figure 15:** The left images shows fitness objective 4 and right images shows darker cells illustrate the blocked views.

Given the complexity of the design problem, the experiment was limited to 25 individuals per generation with a total number of 300 generations.



**Figure 16:** Illustration of the relationship between genes, fitness objectives and morphological attributes of the phenotype.

## 7 RESULTS

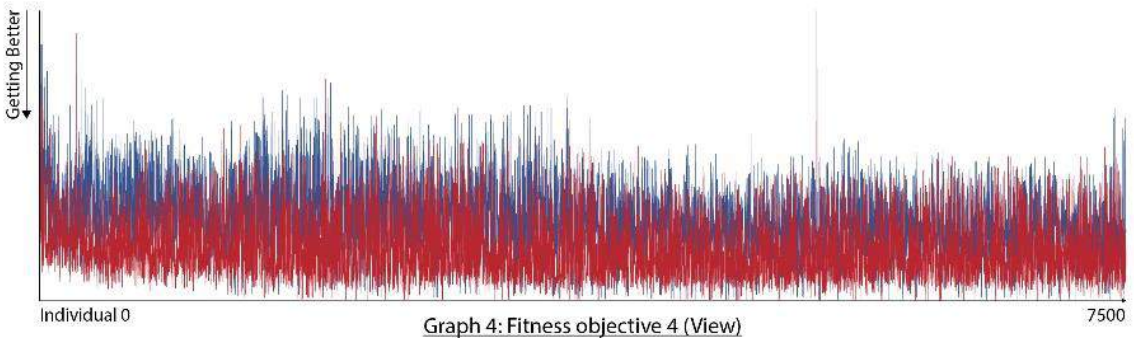
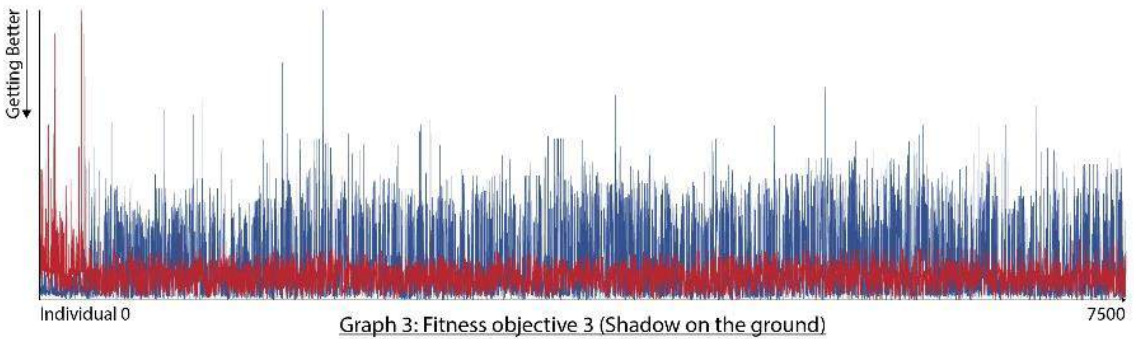
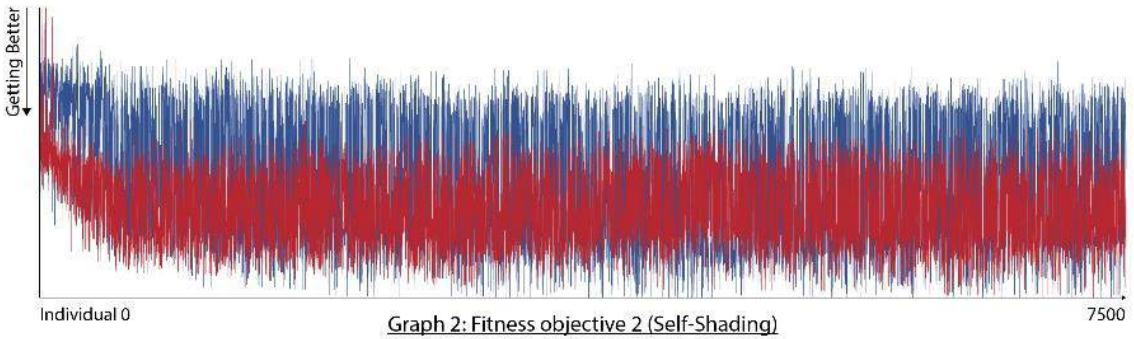
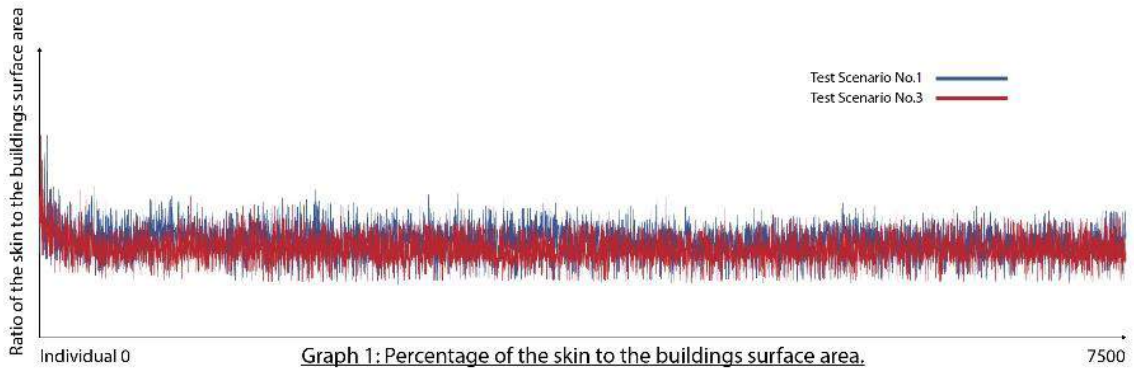
### 7.1 Ablation Study

Five test scenarios with the same algorithmic settings as Table 1 have been conducted to study to what extent the added homeostatic mechanisms will influence the evolutionary simulation. Due to the algorithmic complexity and the required computational power, the size of the simulation (both geometrically and algorithmically) has been reduced by 70% for ablation study. As it is illustrated in Table 7, five scenarios are compared through multiple measurement criteria. It is worth mentioning that the necessary adjustments were made to the calculation of the fitness objectives to ensure a meaningful investigation.

According to the results in Table 7, the performance of simulation No. 3 is very close to the performance of simulation No. 1. Simulations No. 2 and No. 4 due to the absence of F () and G (), are missing the skin system on the form, while in simulation No. 5, due to the lack of F () while executing G(), the skin is excessively applied to the entire phenotype. Further analysis of the simulations No. 1 and No. 3 illustrates that the performance of No. 3 in optimizing the fitness objectives while having less skin is better than that of No. 1 (Figure 17). Consequently, having better values in fitness objectives 2 and 3 (self-shading and shadow on the ground) contributes to better adaptation to the solar radiation in the region.

Tests	H-M-A	H-M-B	Hyper volume Indicator[5]	Pareto Fronts	% Skin (Last 50 gen)	FO 1 Explored Domain	FO 2 Explored Domain	FO 3 Explored Domain	FO 4 Explored Domain	Time Second Per solution
No. 1	Active	Inactive	0.927349572	725	%31.72	23545.73 to 51248.92	1.31 to 1.83	1.55 to 83.24	1.05 to 1.49	4
No. 2	Inactive	Active	0.3946202207	133	%0	29282.68 to 51248.92	1.54 to 2.62	1.71 to 34.30	1 to 1	1
<b>No. 3</b>	<b>Active</b>	<b>Active</b>	<b>0.897516776</b>	<b>751</b>	<b>%30.17</b>	<b>23380.43 to 51350.63</b>	<b>1.32 to 1.97</b>	<b>1.6 to 18.35</b>	<b>1.07 to 1.61</b>	<b>3</b>
No. 4	Inactive	Inactive	0.4227436065	309	%0	24966.40 to 52165.65	1.65 to 2.47	1.66 to 38.73	1 to 1	1
No. 5	Half Inactive	Inactive	0.9383370507	750	%100	23525.34 to 51984.66	1.87 to 24.50	1.26 to 4.64	1.49 to 2.58	7

**Table 7:** Ablation study results.



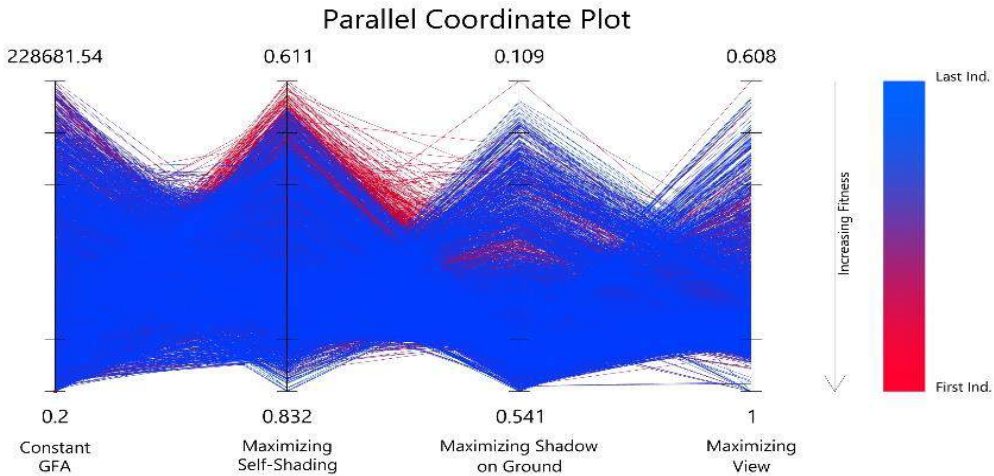
**Figure 17:** Graph 1 shows the ratio of the skin to the entire buildings in each iteration. Test scenario 3 generated slightly less skin on the buildings compare to test scenario 1. Graphs 2, 3 and 4 show the test scenario 3 is performing better in generating solutions with better fitness objetices.



## 7.2 The Main Simulation Run

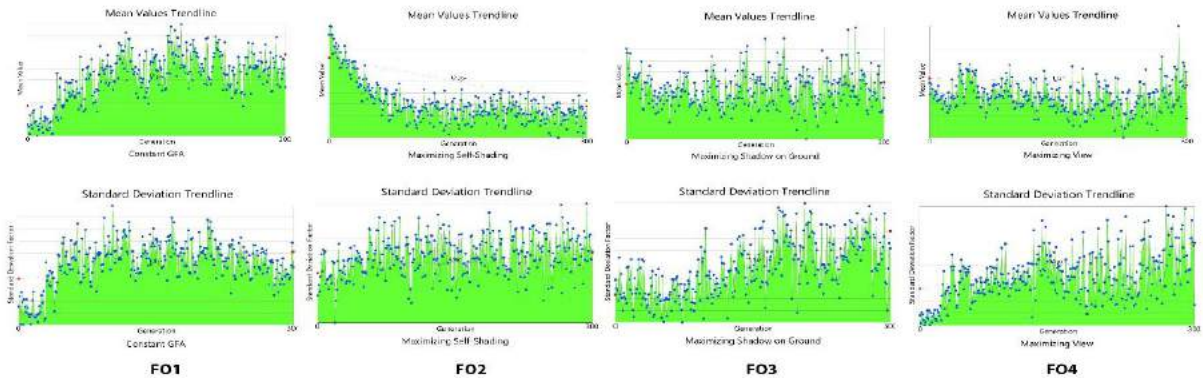
### 7.2.1 Evolutionary simulation

By running the evolutionary simulation for the main design problem, 7500 genotypes/phenotypes with four fitness values per solution were produced. The visual analysis of the results is not sufficient; thus, analysis of the data associated with each phenotype plays a significant role in the selection and comparison of the optimal solutions to the case study. The first set of analysis was performed to understand the simulation in its entirety. The performance of each fitness objective is shown in Figure 18 in the parallel coordinate plot where each line represents a solution, and each axis represents an objective.



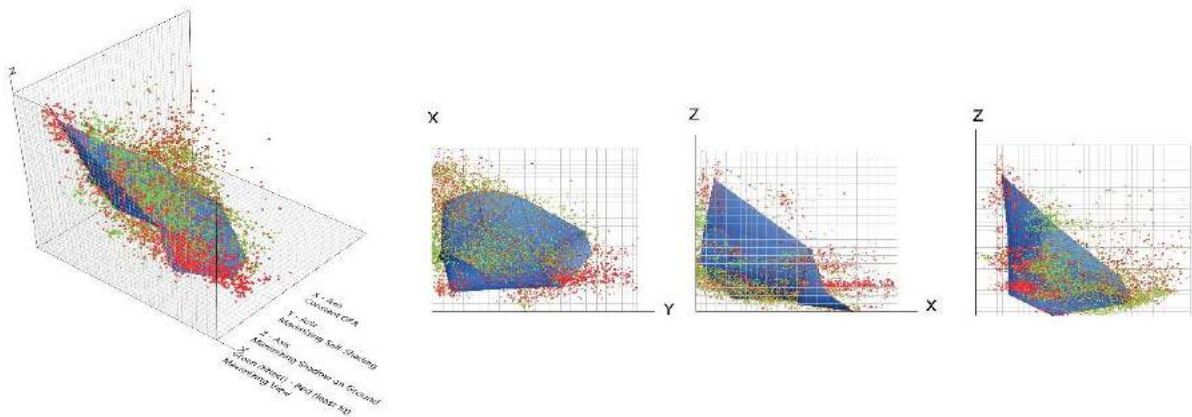
**Figure 18:** This figure shows the relationship between the fitness objectives of each solution. From top to bottom, fitness values are getting better. The colour red to blue illustrates the beginning to the end of the simulation.

Simulation explored a wide range of solutions throughout the process, which is indicative of fitness objectives conflicting with one another — comparing the performance of each fitness criteria side by side by plotting their mean values per generation, together with their standard deviation factors confirms this observation (Figure 19).



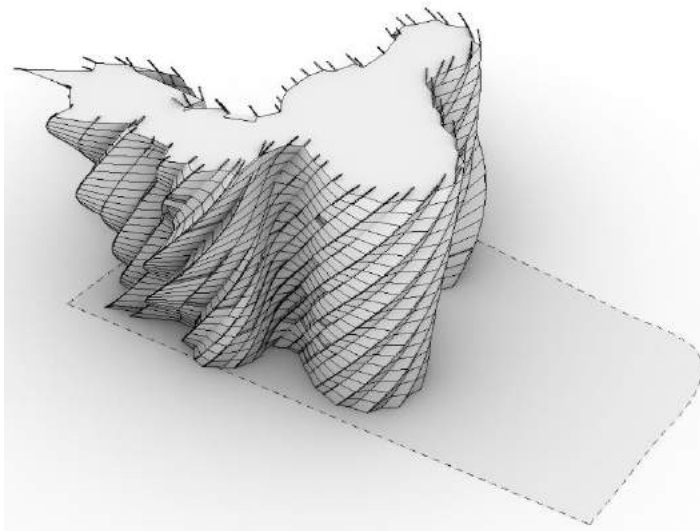
**Figure 19:** Standard deviation and average fitness value per generation graphs for all fitness objectives.

As the simulation progressed, it produced solutions with GFA farther from the case study (FO1). Simulation performed well for creating solutions with self-shading attributes by increasing the number and the depth of the indentations as well as the juxtaposition of the buildings relative to one another. However, the variation in this objective increased as the simulation progressed. FO3 and FO4 display that the simulation struggled to optimize the third and fourth fitness criteria; however, it produced a significant amount of variations. With regards to the Pareto Front Solutions, (it is shown as the blue mesh in the objective space in Figure 20), solutions were distributed uniformly throughout the simulation, highlighting the conflict between fitness criteria and an inability for one objective to drive the simulation more than the others.



**Figure 20:** The objective space and the pareto front mesh.

Prior to filtering down the population to select the candidate solutions for comparison to the case studies, it must be noted that 1.5 % of the population (113 individuals out of 7500) were considered anomalies; this was the result of the unsuccessful execution of G () which led to the failure of generating the skin on the buildings (Figure 21).

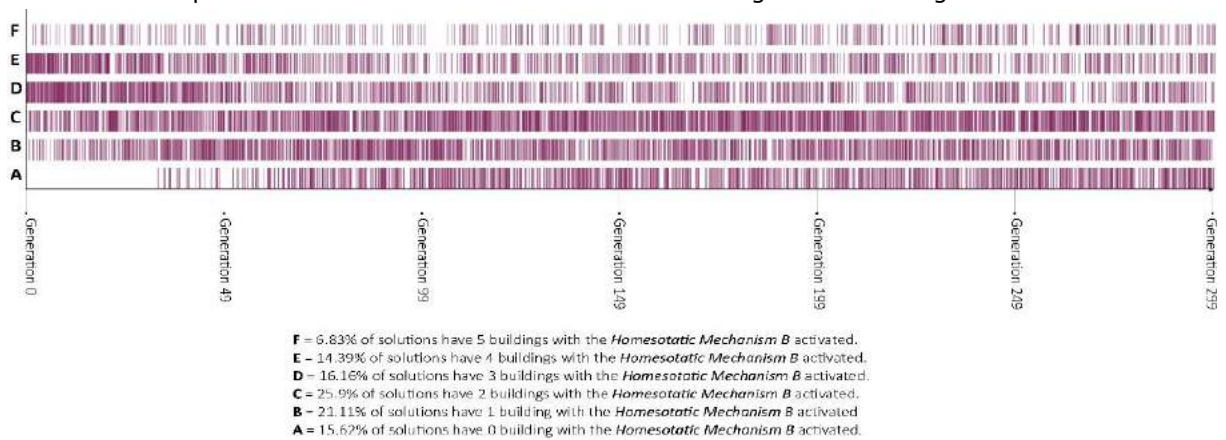


**Figure 21:** An example of an anomaly solution.

7.2.2 Homeostatic Mechanism

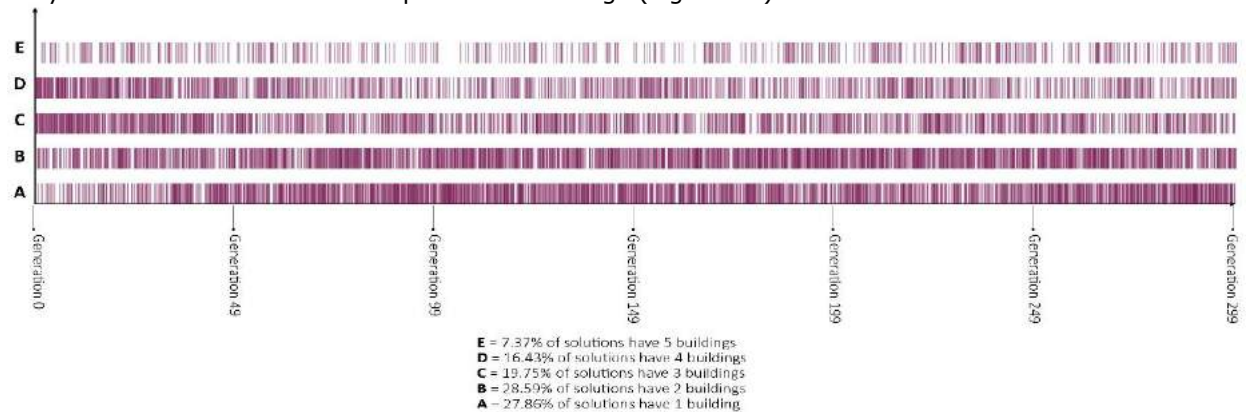
The frequency at which the homeostatic mechanisms have been activated relative to the number of buildings were recorded to understand the efficiency of the proposed methodology in producing morphological characteristics. H-M-A was the primary regulatory system introduced to the simulation to counteract the excessive solar radiation. Except for the anomalies (Figure 21), this regulatory mechanism was activated successfully and created a reference point for change in the evolutionary simulation. Evolved phenotypes all possess this formal attribute (skin).

Figure 22 and Figure 23 illustrate the frequency of the activation of H-M-B relative to the number of buildings evolved in the simulation. Figure 22 shows that in 15.62% of the solutions, situated after generation 49, H-M-B was not activated. It is understood that up until generation 49, the simulation was favouring the activation of H-M-B; however, after generation 49, it started to explore solutions with no such formal attribute. According to Figure 22, 25.9% (the highest rate) of solutions have two buildings with the formal attribute of H-M-B. The low number of solutions, 6.83%, with five buildings with the quality of H-M-B is indicative that solutions with more buildings have less surface area exposed to the solar radiation due to self-shading of the buildings onto one another.



**Figure 22:** This figure illustrates the frequency of which H-M-B has been activated throughout the simulation in relation to the number of buildings.

The frequency of the number of buildings in each solution shows that simulation favours solutions with one or two buildings which are a total of 56.45% of the solutions generated in the simulation. Only 7.37% of the solutions comprise five buildings (Figure 23).



**Figure 23:** This figure illustrates the frequency of how many buildings in a building cluster have been generated throughout the simulation.

Six solutions from 7500 phenotypes were selected to study how successful or unsuccessful the simulation was in optimizing, and how much better or worse they performed compared to the case studies in adapting to the excessive solar radiation of the Persian Gulf region. To select a set of candidate solutions in the multi-objective evolutionary algorithm while limiting the user's preference is a challenging task. To compare a wide range of solutions to the case studies, 4 out of 6 selected solutions are the best options for each of the fitness objectives. The fifth and the sixth are the solutions which addressed the fitness objectives equally. The fifth has the highest average fitness rank amongst 7500 solutions (for further description of the selection strategies, please refer to [20]) and the sixth addresses all objectives as equal as possible. Each solution is accompanied by a full Wallacei analysis and the illustration of their morphological properties. The investigation of each selected solution continues by studying how successfully or unsuccessfully they performed in the following measurement criteria in comparison to the case studies:

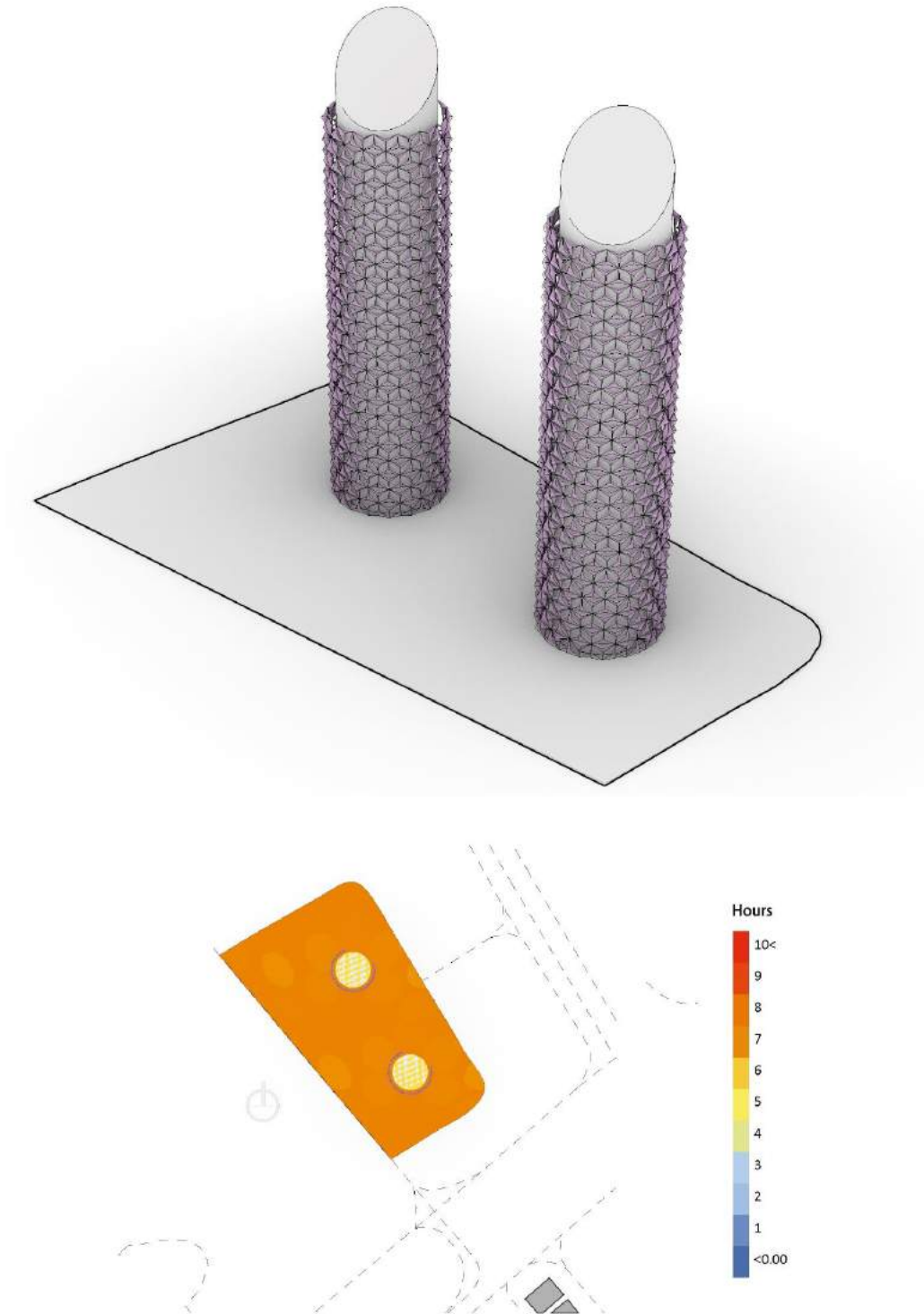
- What percentage of the building surface area will receive more than the threshold of 2 KwH/m<sup>2</sup> solar radiation? Due to the chosen date of the analysis (June 21), the sun angle is vertical to the buildings, and the roofs receive most of the solar radiation. However, in the experiments presented in this paper, the roof was not considered in the solar radiation analysis. According to the annual maximum solar gain in Abu-Dhabi [40], 6.3 KwH/m<sup>2</sup> is the maximum solar gain per day in a year. Since neither the Al-Bahr Towers nor the selected solutions will receive this much solar radiation (without considering the roofs), the figure 1 KwH/m<sup>2</sup> is chosen by the authors to conduct a meaningful comparison between the Al-Bahr Towers and the selected solutions. This analysis demonstrates how well the evolved morphological attributes of the phenotypes obstruct the solar radiation exposed to the building surfaces relative to the case studies.
- How much does the evolved skin system obstruct the view from inside to outside of the buildings? Increasing the view as a fitness objective was introduced to the simulation to make sure that the skin contributes to the obstruction of the solar radiation while maintaining a degree of freedom of view from inside to outside of the buildings. To conduct a meaningful analysis between the selected solutions and the case studies, the frame of the skin systems in all cases (case studies and selected candidates) are the only obstructing geometry for calculating the view.
- How well do the selected solutions provide shading on the ground for outdoor activities?

In all three measurement criteria, selected candidates perform better than the case studies while exhibiting a wide range of morphological variations. All the selected phenotypes have H-M-A (skin system) activated while H-M-B (protrusions) was triggered selectively (refer back to the frequency analysis). The percentage of the building cluster surface area that receives solar radiation more than the threshold is less than in the Al-Bahr Towers (for all solutions except one). All the selected solutions successfully created pockets of shadow on the ground which facilitate outdoor activities, an attribute that is missing in the case studies. The selected solutions display advantages in facilitating the view from inside to the outside of the buildings when compared to the case studies. (Analysis are illustrated in Figure 24, Figure 25, Figure 26, Figure 27, Figure 28, Figure 29, Figure 30, Figure 31, Figure 32, Figure 33, Figure 34, Figure 35, Figure 36, Figure 37) (shadow analysis was conducted by Ladybug tools [29]).

## 8 DISCUSSION

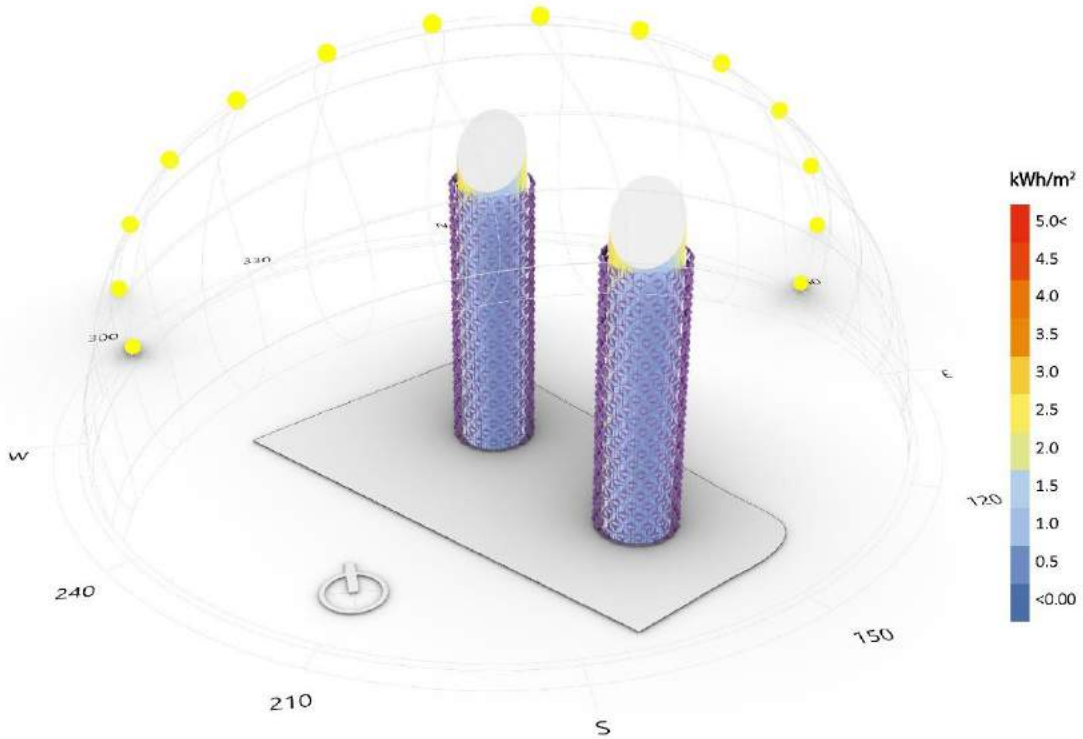
Extreme solar radiation in the areas such as the Persian Gulf region leads to the employment of expensive temperature regulatory mechanisms within the buildings and contributes to high energy usage. This excessive use of energy directly or indirectly influences CO<sub>2</sub> emissions and subsequently causes temperature rise and global warming.



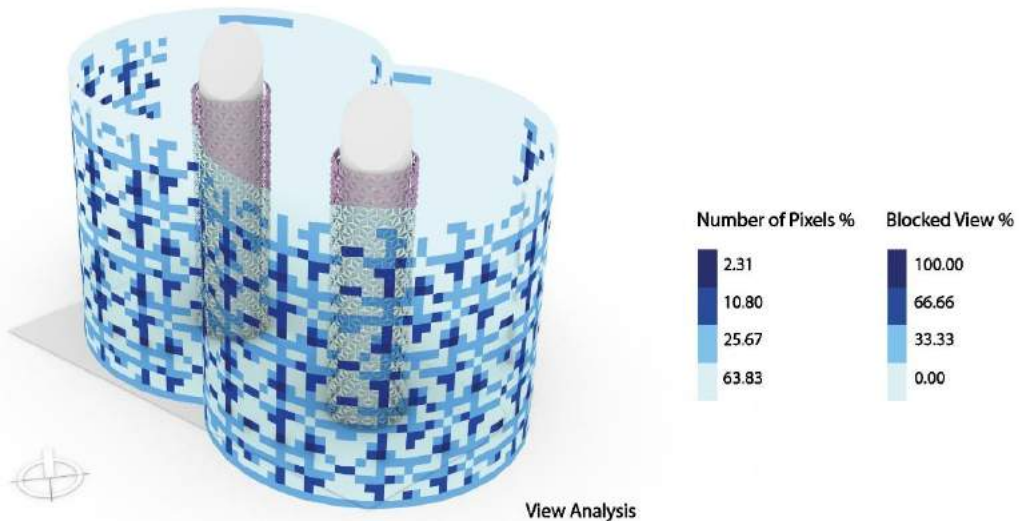


**Figure 24:** Solar radiation analysis (shadow on the ground) of the Al-Bahr Towers (All solar radiations are carried out by Ladybug Tools [29]).

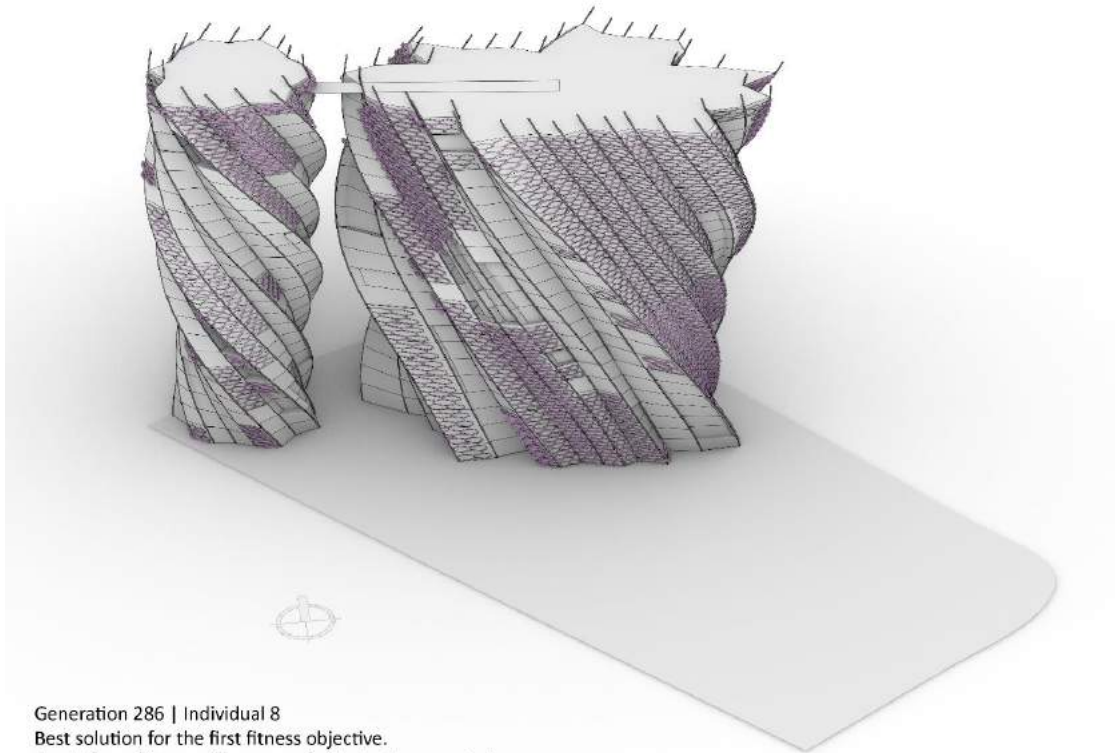




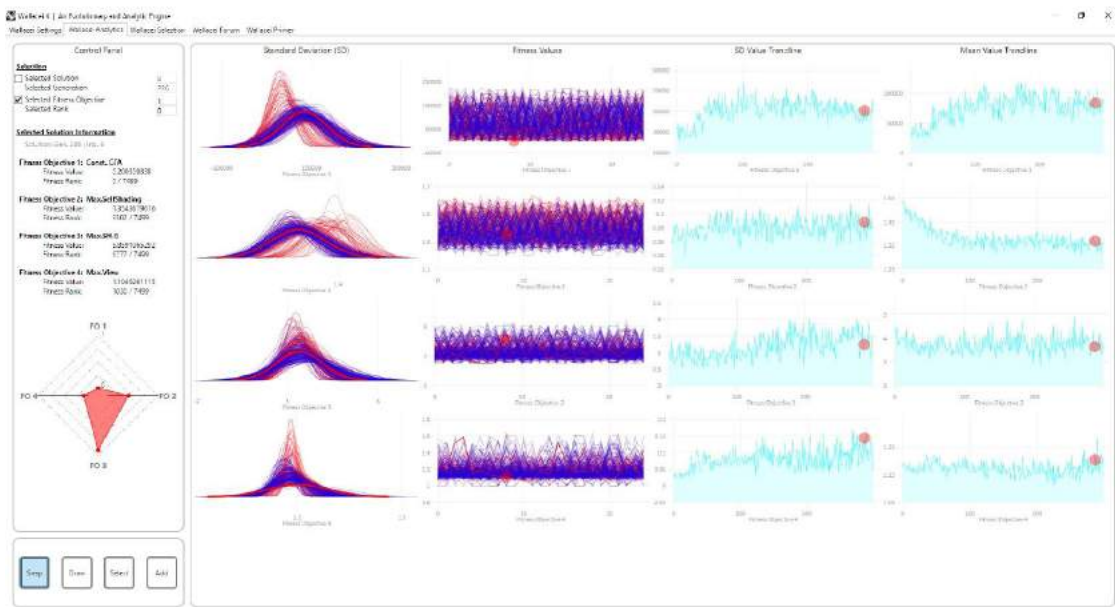
Radiation Analysis  
 Abu Dhabi 21 June 1:00 to 21 June 24:00  
 20.00 % of the buildings' surface area receives more that  
 2 Kwh/m2 solar radiation



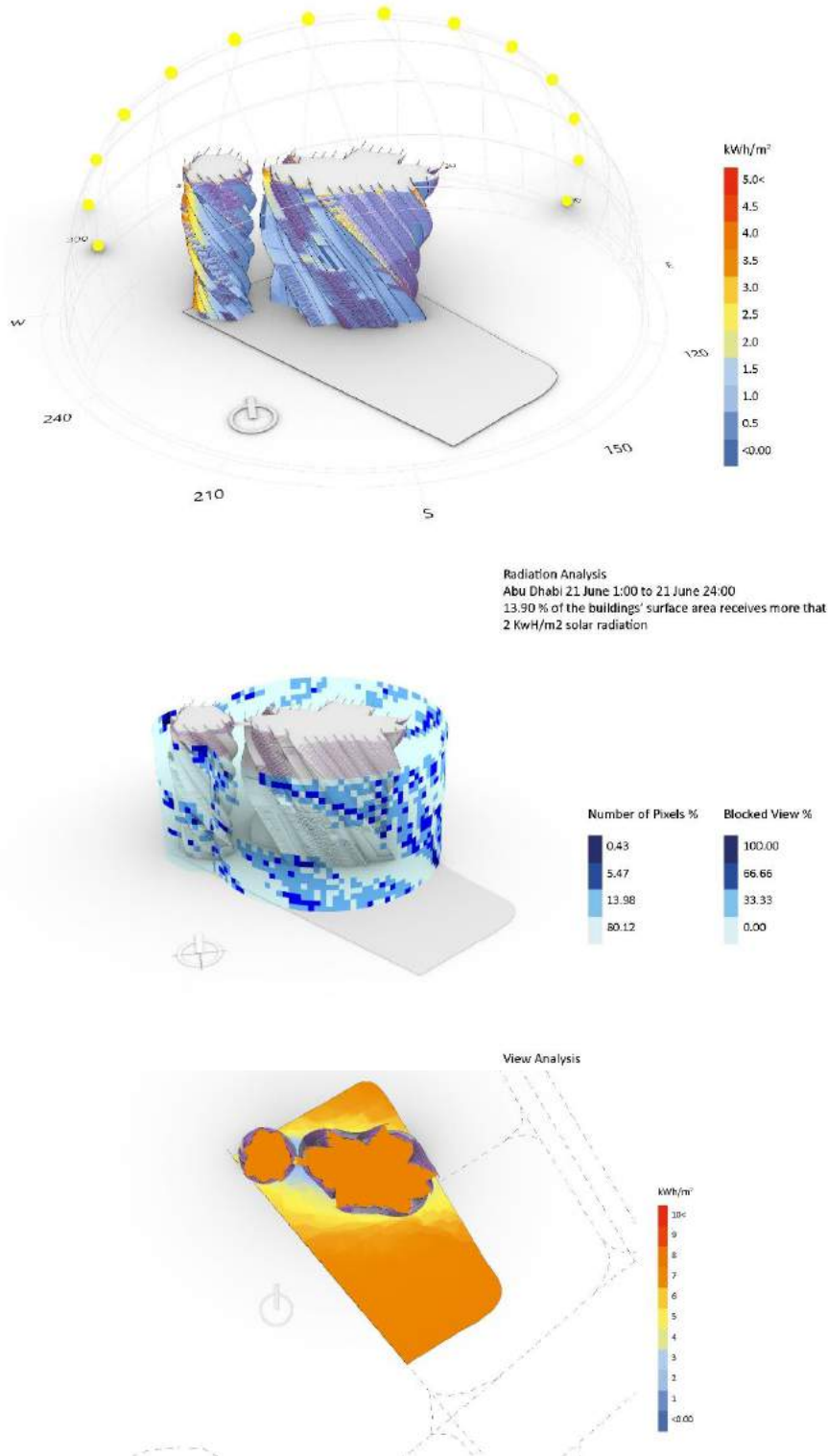
**Figure 25:** This figure shows the measurements based on which the case studies will be compared to the generated solutions. The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m2 solar radiation. The bottom drawing presents the percentage that the skin blocks the view from inside to outside.



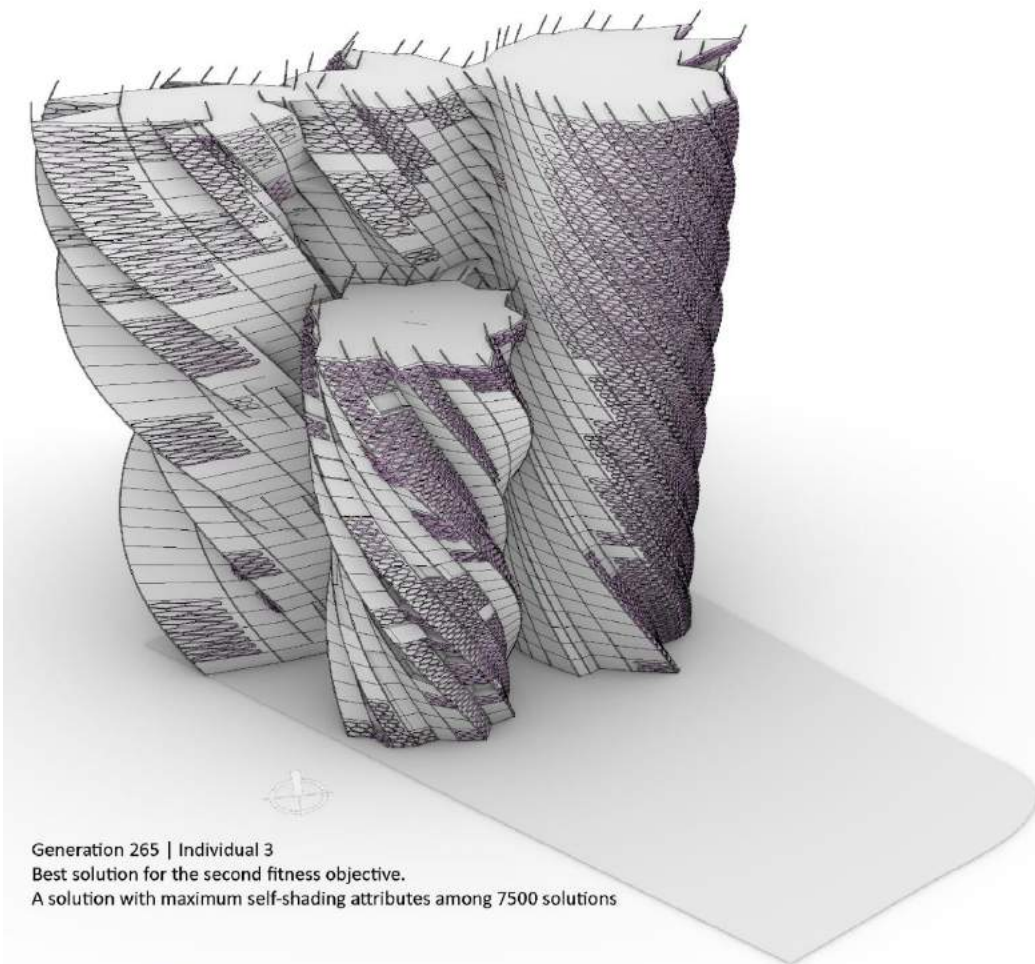
Generation 286 | Individual 8  
 Best solution for the first fitness objective.  
 A solution with gross floor area similar to the case study



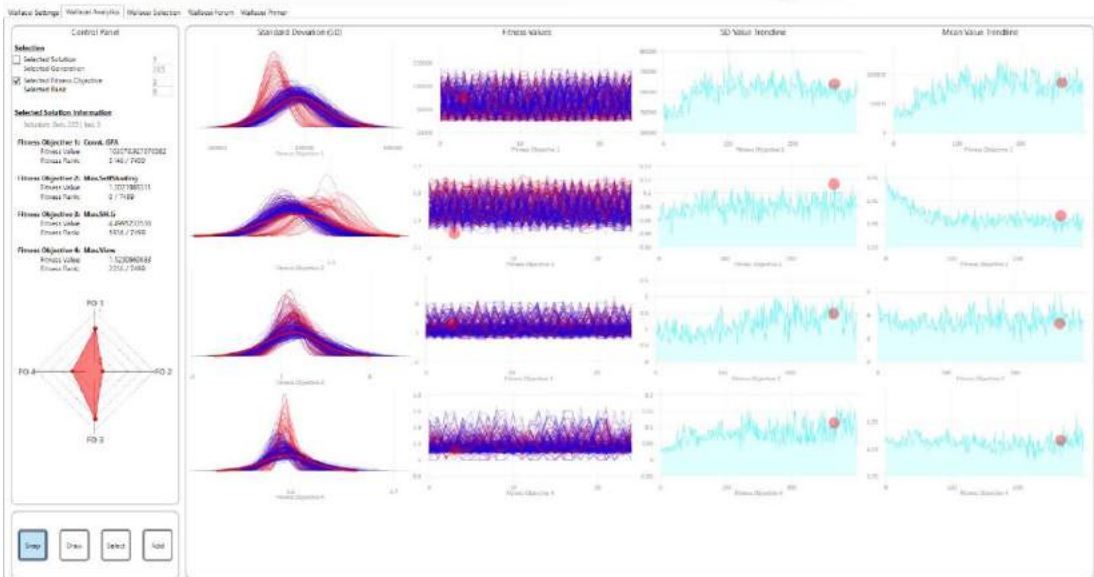
**Figure 26:** First selected solution. The graphs plot all four fitness objectives next to one another. The red dots and curves show the selected solution in the entire simulation. It shows how successfully or unsuccessfully simulation optimized this solution for the four fitness objectives. For a description of the graphs please refer to (36).



**Figure 27:** Continuation of Figure 26. From top to bottom i) The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m<sup>2</sup> solar radiation. ii) the middle drawing presents the percentage that the skin blocks the view from inside to outside iii) Solar radiation analysis (shadow on the ground).

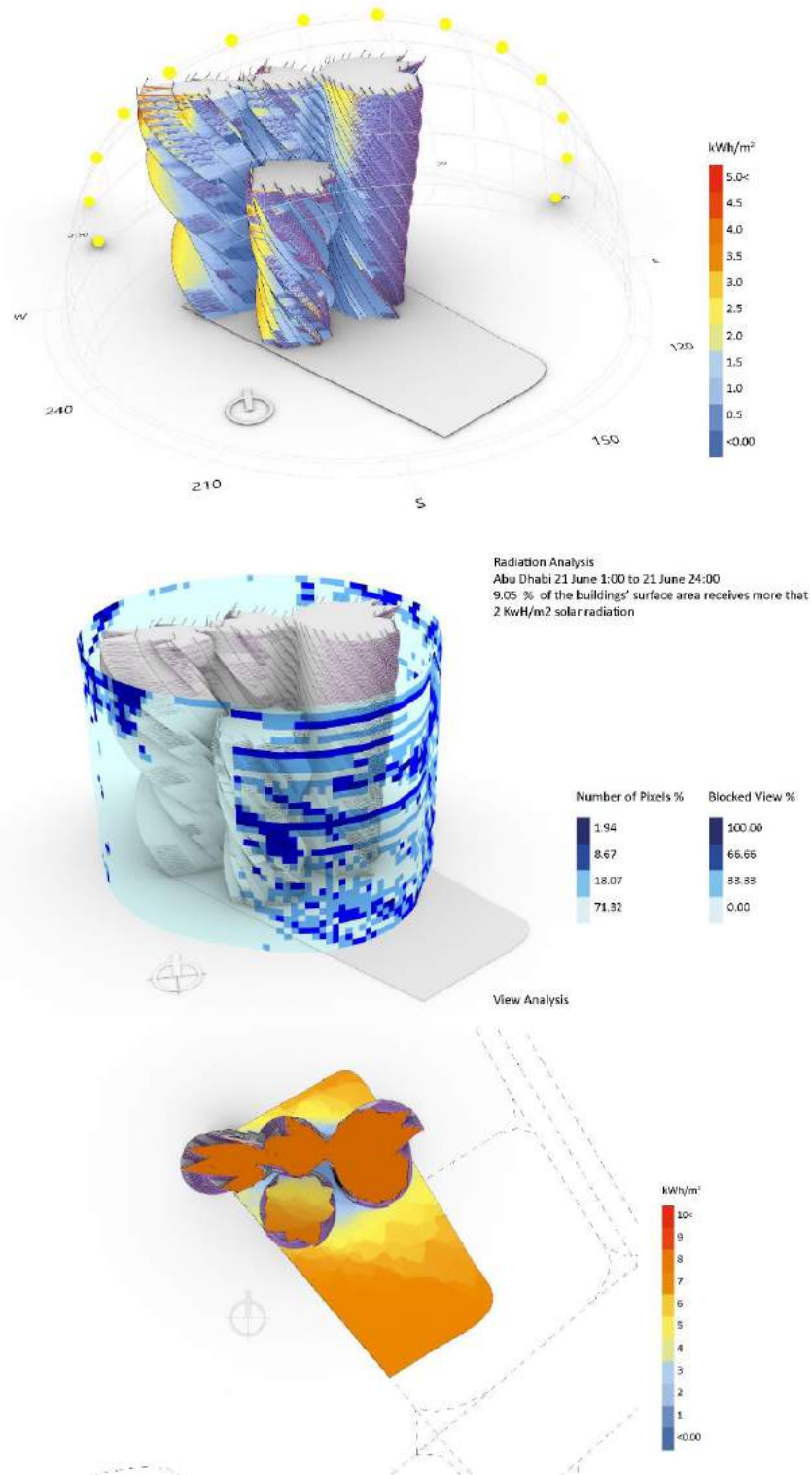


Generation 265 | Individual 3  
 Best solution for the second fitness objective.  
 A solution with maximum self-shading attributes among 7500 solutions



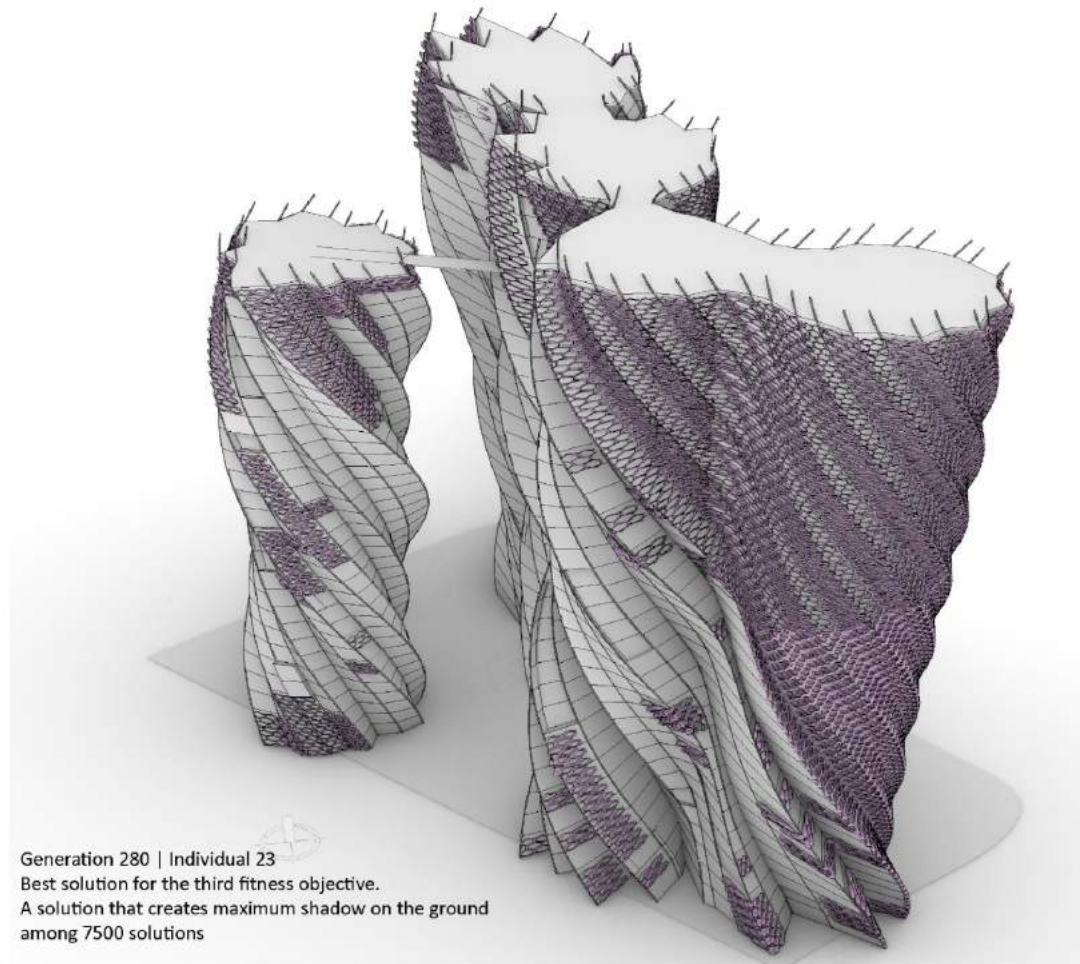
**Figure 28:** Second selected solution. The graphs plot all four fitness objectives next to one another. The red dots and curves show the selected solution in the entire simulation. It shows how successfully or unsuccessfully simulation optimized this solution for the four fitness objectives.



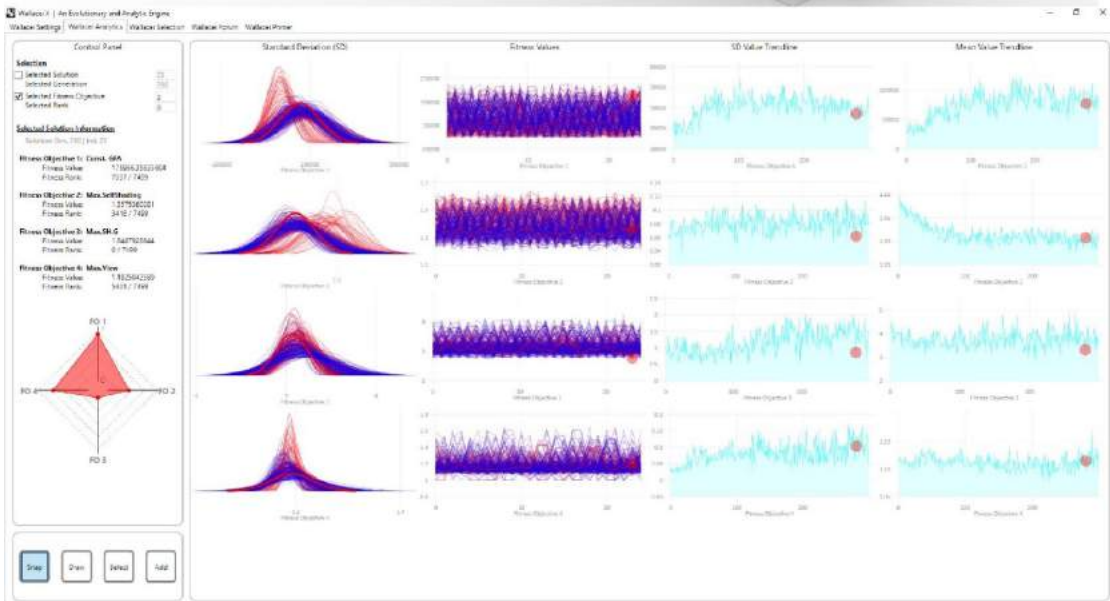


**Figure 29:** Continuation of figure 28 From top to bottom i) The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m2 solar radiation. ii) the middle drawing presents the percentage that the skin blocks the view from inside to outside iii) Solar radiation analysis (shadow on the ground).

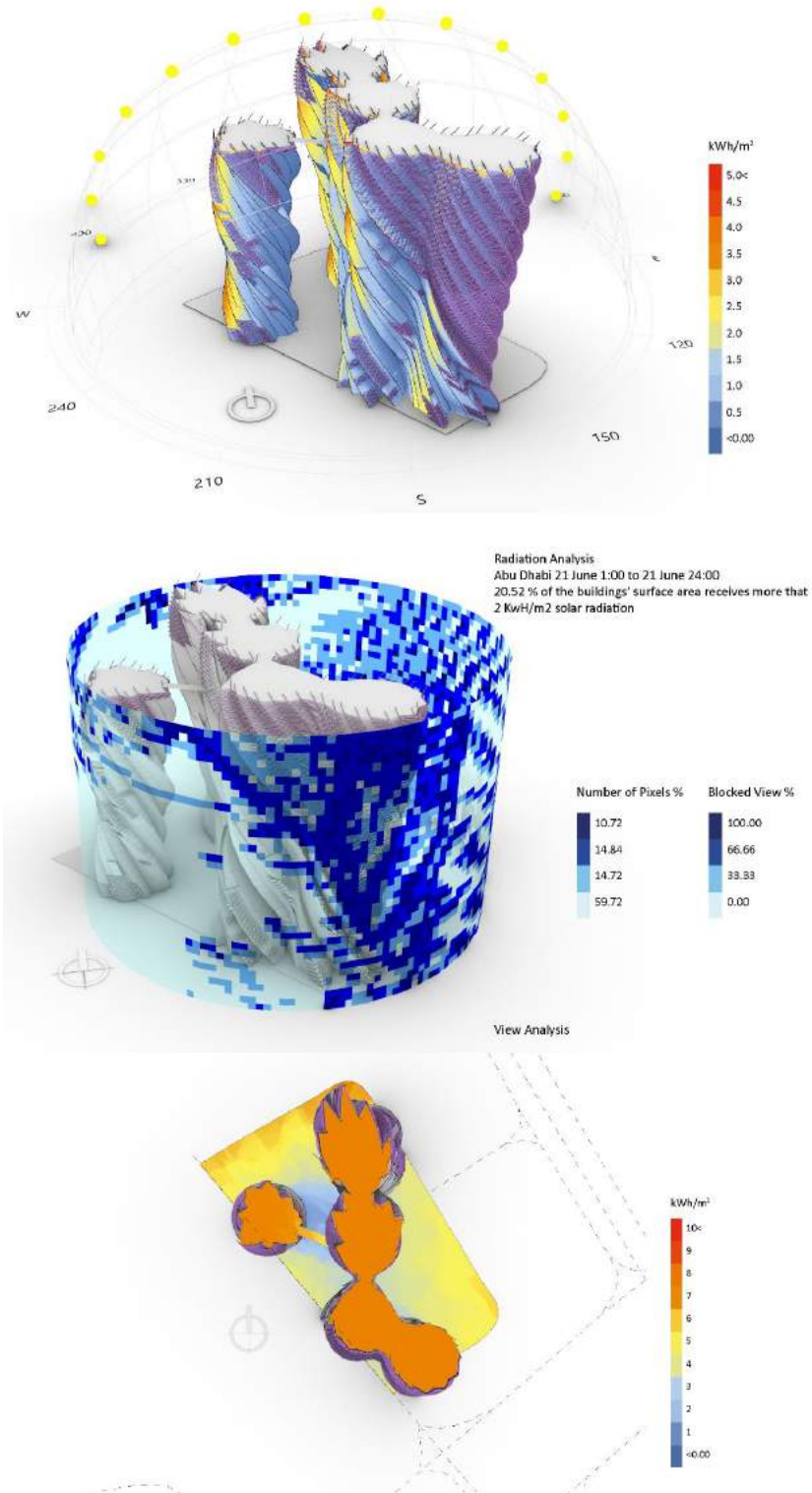




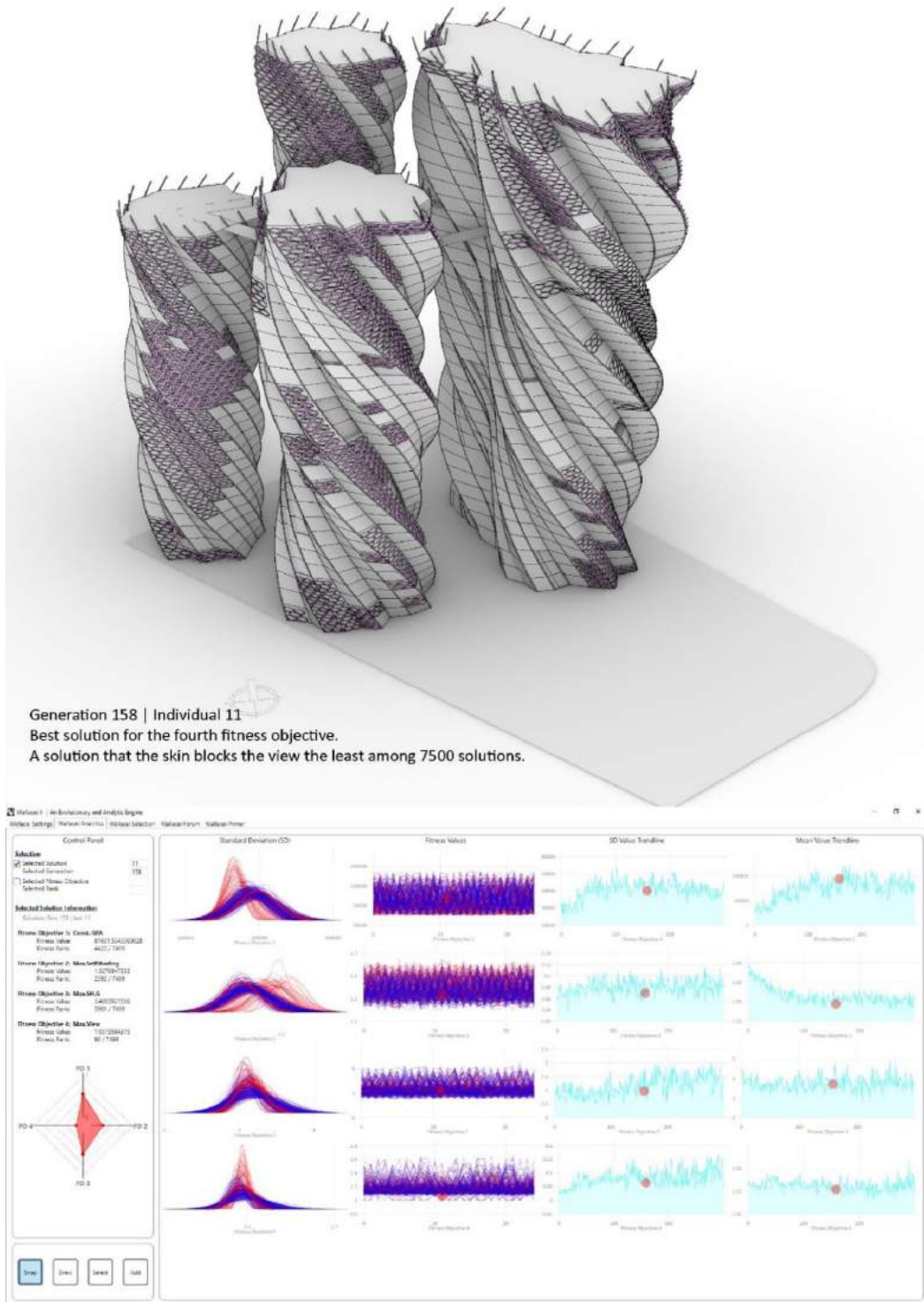
Generation 280 | Individual 23  
 Best solution for the third fitness objective.  
 A solution that creates maximum shadow on the ground  
 among 7500 solutions



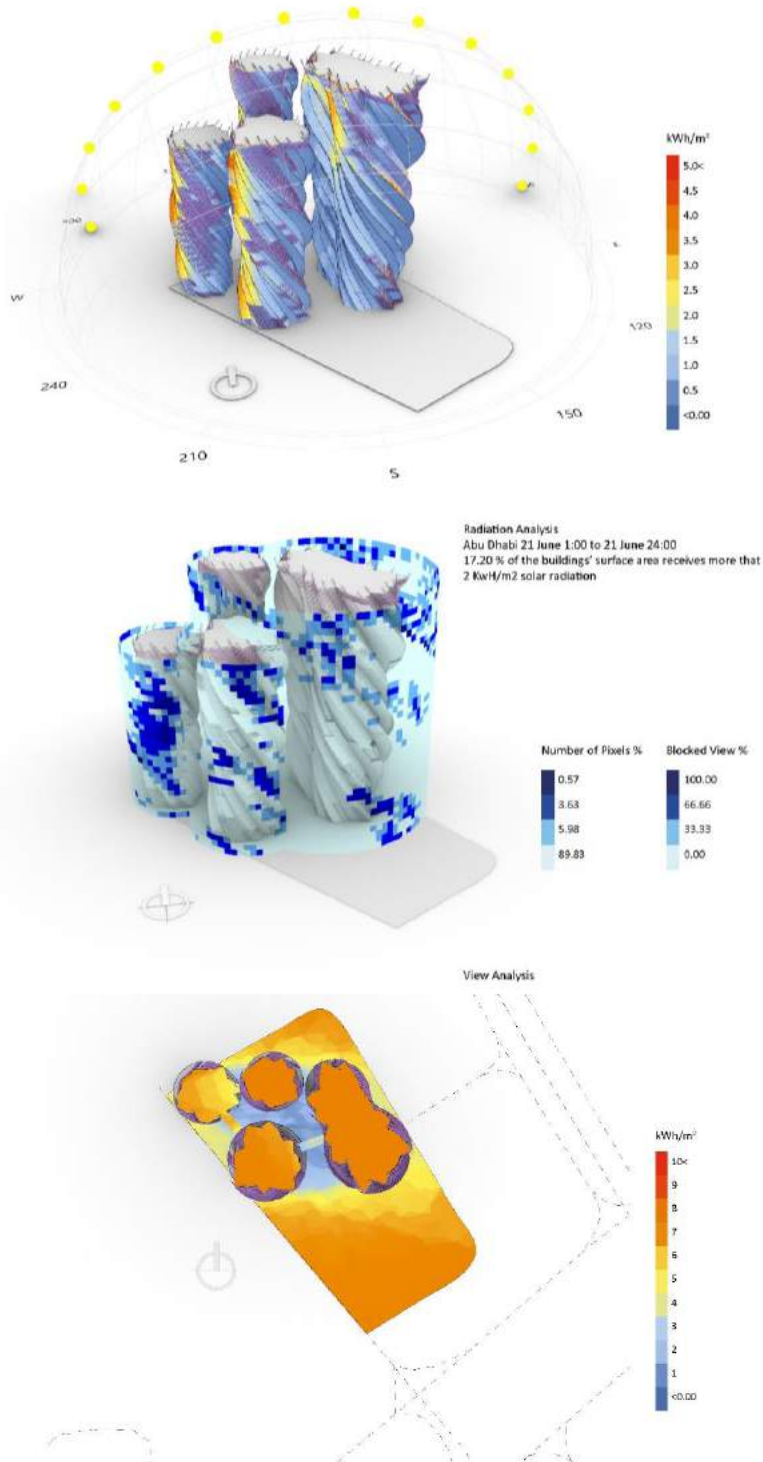
**Figure 30:** Third selected solution. The graphs plot all four fitness objectives next to one another. The red dots and curves show the selected solution in the entire simulation. It shows how successfully or unsuccessfully simulation optimized this solution for the four fitness objectives.



**Figure 31:** Continuation of figure 30. From top to bottom i) The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m<sup>2</sup> solar radiation. ii) the middle drawing presents the percentage that the skin blocks the view from inside to outside iii) Solar radiation analysis (shadow on the ground).

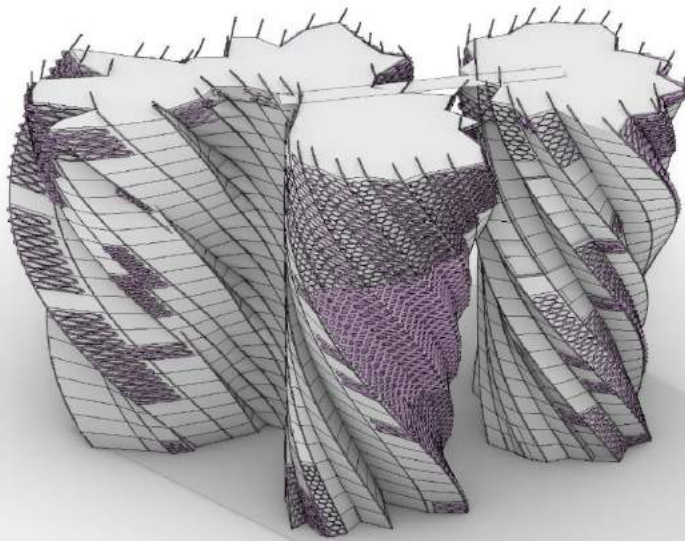


**Figure 32:** Fourth selected solution. The graphs plot all four fitness objectives next to one another. The red dots and curves show the selected solution in the entire simulation. It shows how successfully or unsuccessfully simulation optimized this solution for the four fitness objectives.

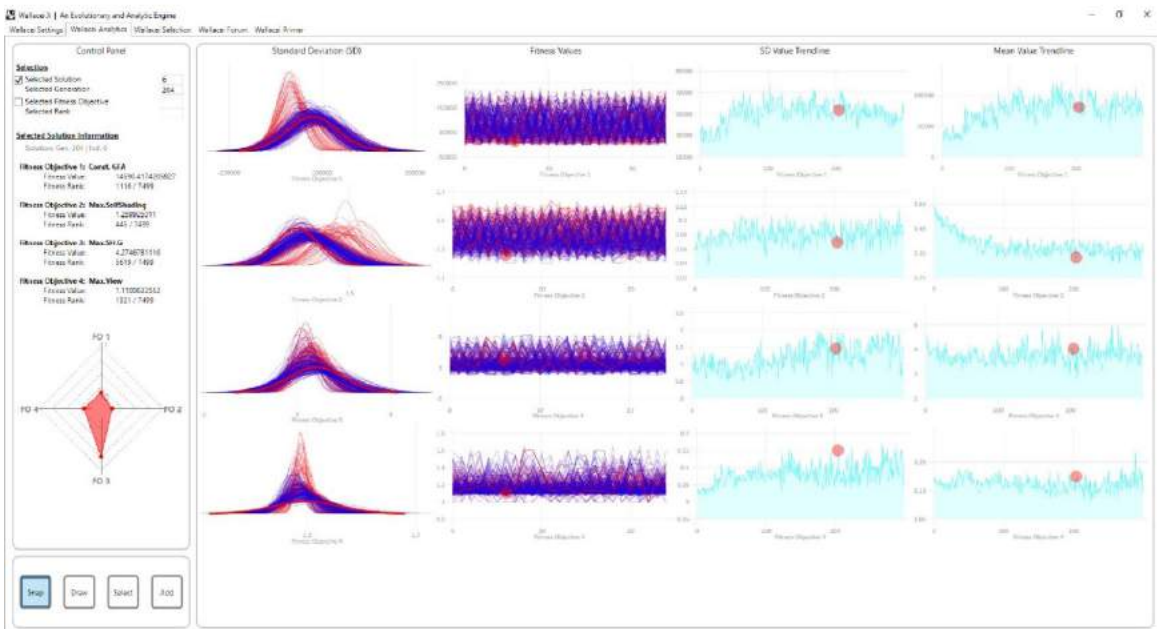


**Figure 33:** Continuation of figure 32, From top to bottom i) The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m<sup>2</sup> solar radiation. ii) the middle drawing presents the percentage that the skin blocks the view from inside to outside iii) Solar radiation analysis (shadow on the ground).



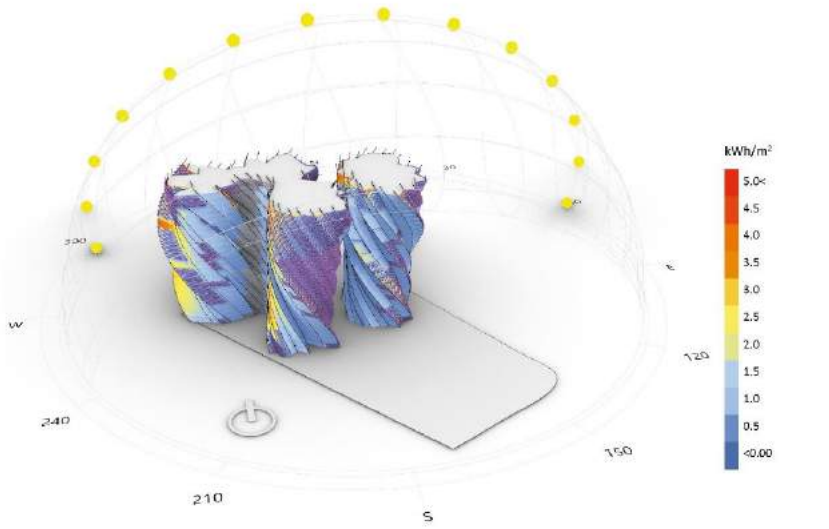


Generation 204 | Individual 6  
 Solution with the lowest averaged fitness rank among 7500 solutions

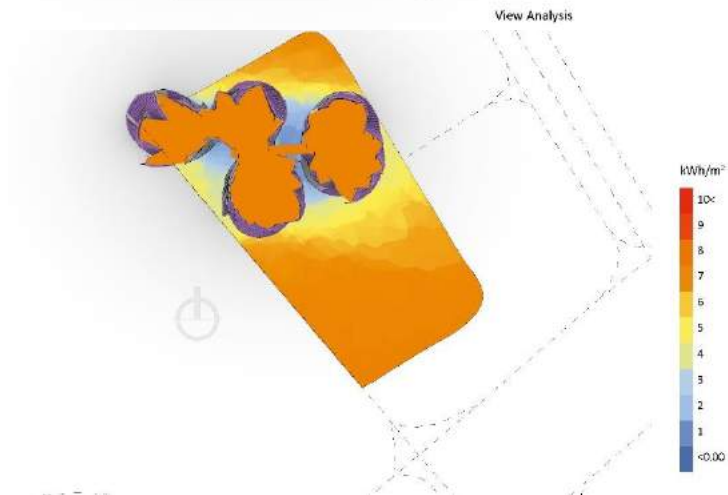
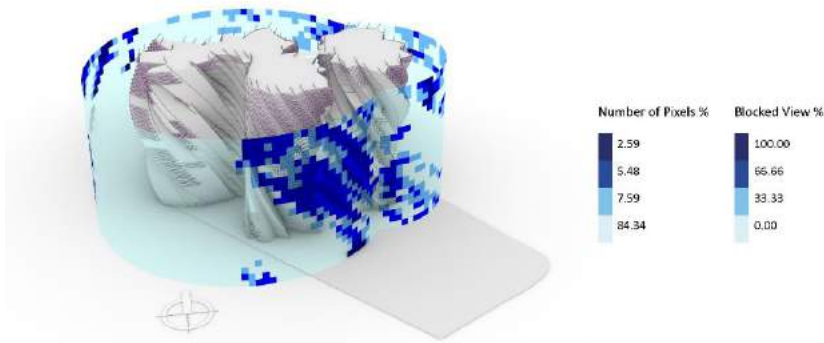


**Figure 34:** Fifth selected solution, the graphs plot all four fitness objectives next to one another. The red dots and curves show the selected solution in the entire simulation. It shows how successfully or unsuccessfully simulation optimized this solution for the four fitness objectives.

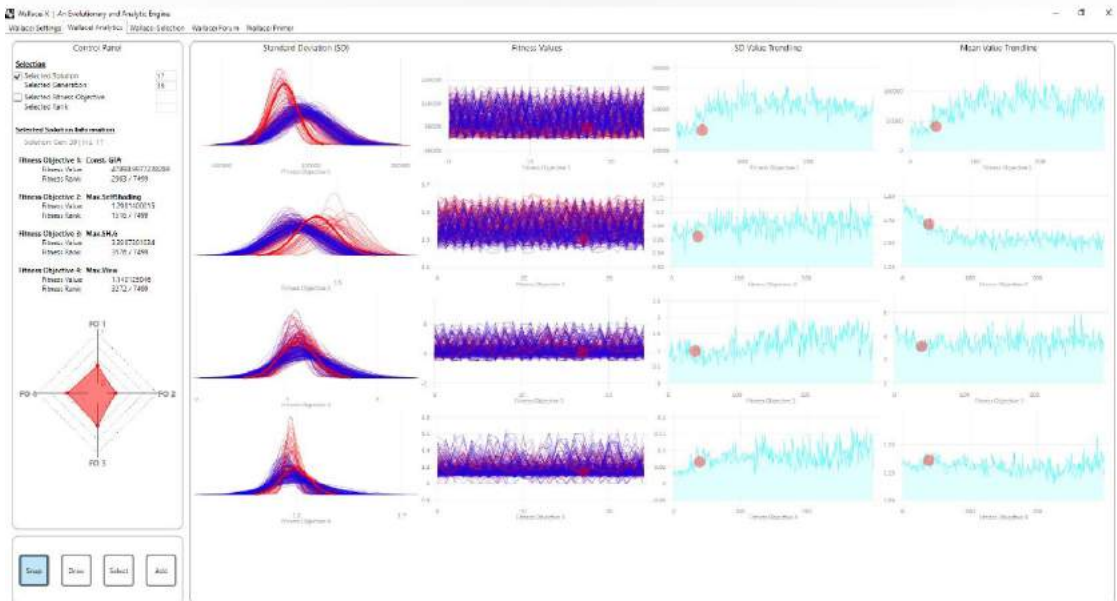
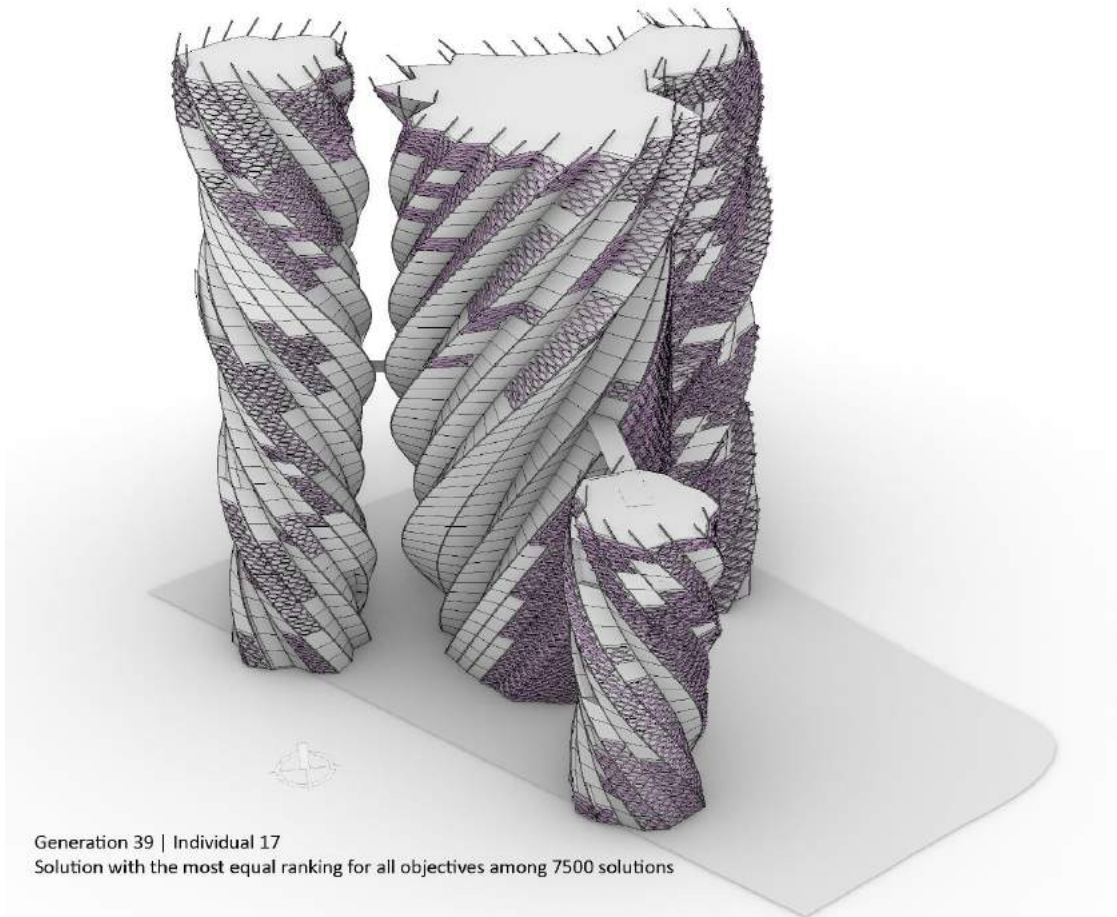




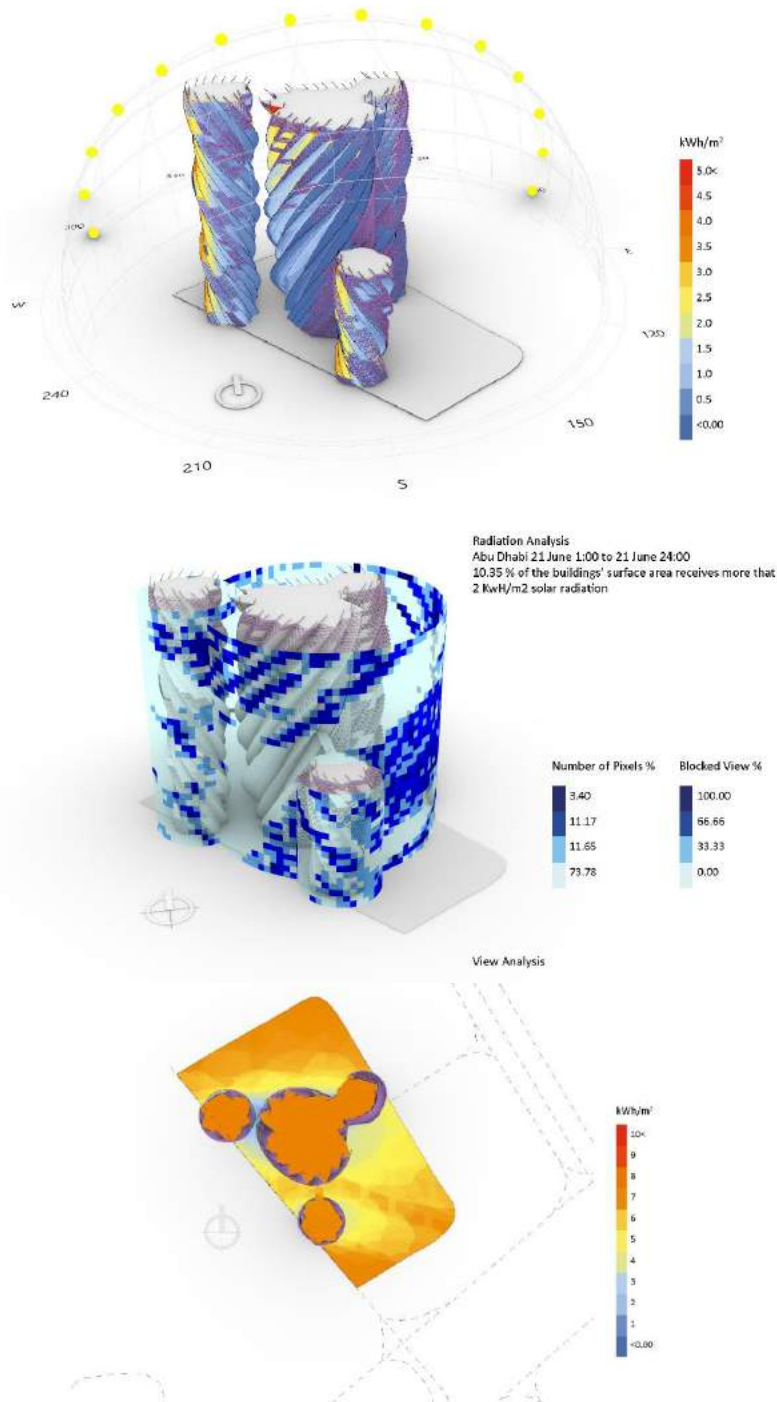
Radiation Analysis  
 Abu Dhabi 21 June 1:00 to 21 June 24:00  
 12.81 % of the buildings' surface area receives more than 2 kWh/m<sup>2</sup> solar radiation



**Figure 35:** Continuation of figure 34 From top to bottom i) The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m<sup>2</sup> solar radiation. ii) the middle drawing presents the percentage that the skin blocks the view from inside to outside iii) Solar radiation analysis (shadow on the ground).



**Figure 36:** Sixth selected solution. The graphs plot all four fitness objectives next to one another. The red dots and curves show the selected solution in the entire simulation. It shows how successfully or unsuccessfully simulation optimized this solution for the four fitness objectives.



**Figure 37:** Continuation of figure 36. From top to bottom i) The top drawing illustrates what percentage of the building surface area receives more than 2 Kwh/m2 solar radiation. ii) the middle drawing presents the percentage that the skin blocks the view from inside to outside iii) Solar radiation analysis (shadow on the ground).

Species throughout their evolution have evolved unique responsive behaviors, processes and morphological characteristics that enable their survival and adaptation to environmental changes. Authors of this paper, through investigating the unique biological principles and means by which species adapt to extreme environmental conditions have put forward a design methodology which highlights the significance of early design explorations in addressing climatic stresses.

The presented experiment in this paper demonstrates an evolutionary design system with additional regulatory mechanisms to generate a building cluster with morphological attributes suitable for adaptation to excessive solar radiation. Homeostatic principles were mapped algorithmically in the evolutionary design system and helped to steer the simulation towards generating morphological attributes embedded in the phenotypes that facilitate a better adaptation to the excessive solar radiation. The design system has provided a comprehensive workflow to implement a set of biological principles of evolution and homeostasis in an architectural generative design process, to evaluate and select the results and to validate the selected design options.

The Al-Bahr Towers, due to their extreme environmental context and the use of contemporary temperature regulatory mechanisms, were chosen as the case studies and reference point for conducting comparisons. As presented in the Results section, the design process successfully generated candidate solutions with diverse morphological characteristics, each of which performs better, based on the measurement criteria, than the case studies. The proposed design system highlights the significance of the formal explorations at the early design phases. The proposed design system produced a significant amount of variations from which a noticeable number of generated options were performing better than the case studies. Figure 38 illustrates six extra individuals from the Pareto front set. As it is shown in the figure and the analysis, these selected solutions are performing better than the Al-Bahr towers in the measurement criteria as well.

Further analysis must be undertaken to determine to what extent this is an effective mechanism to incorporate homeostatic principles in design processes. One of the limitations of this study was the computation time due to the added homeostatic evaluations in the design problem algorithm. It significantly increased the simulation time; however, successfully produced desirable solutions. Authors are currently continuing their research in extending this design methodology to better employ feedback and regulatory mechanisms into the generative design processes to incorporate more architectural parameters such as structural performances.

## 9 FUNDING

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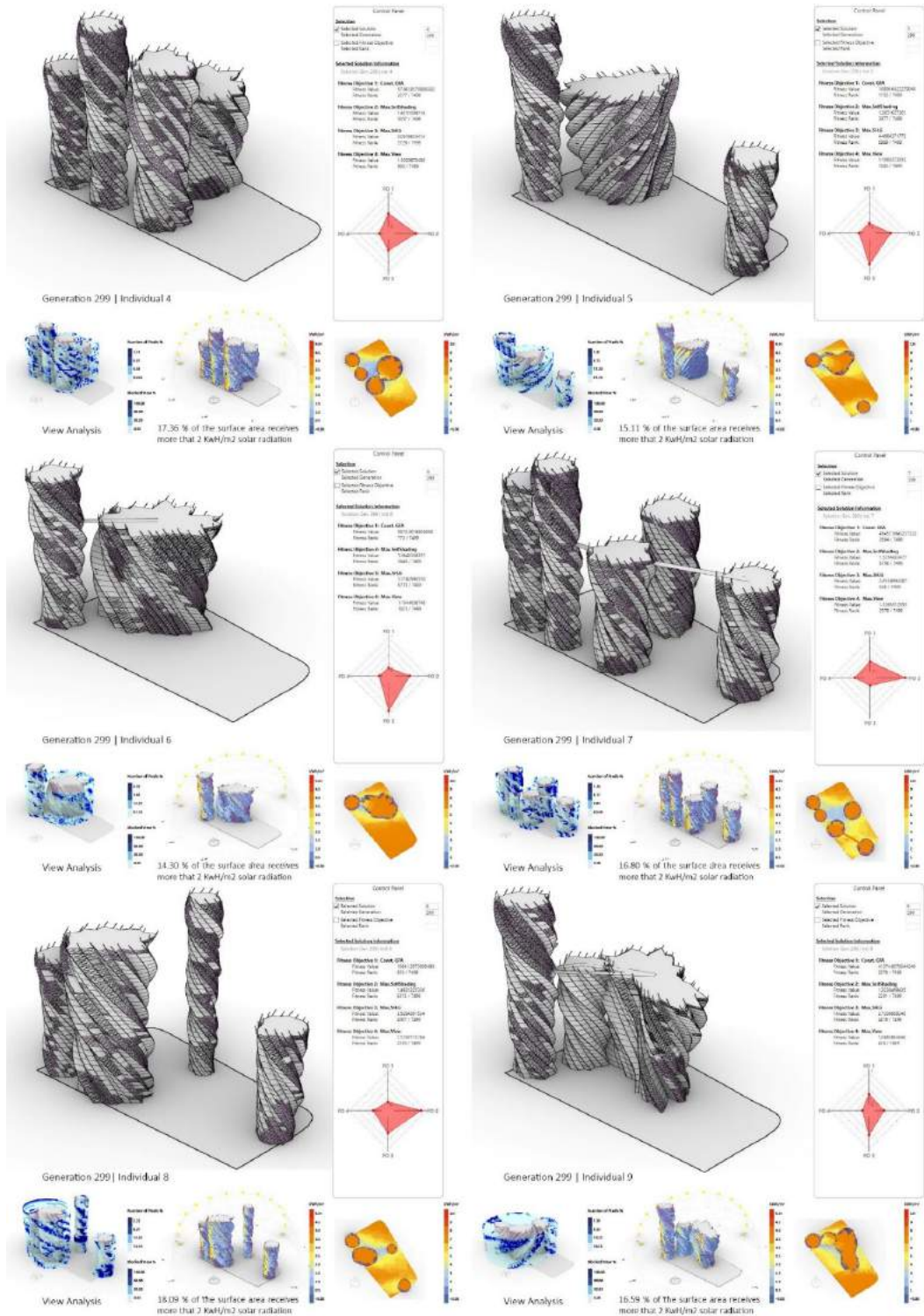
*Milad Showkatbakhsh*, <https://orcid.org/0000-0001-5440-5175>

*Saam Kaviani*, <https://orcid.org/0000-0001-6551-9565>

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**Figure 38:** A selected set of pareto front solutions. The analysis illustrates that these selected candidates are performing better than the case studies as well.



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