Evolutionary Designed Building Skins with Embedded Biomimetic Adaptation Lessons

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Abstract:

The ambition of this study is to create a computational design engine that develops testable simulated models that can adapt to various situations or environments by abstracting some adoption lessons from biology and their relationship to the evolutionary growth of natural systems. With an emphasis on the optimisation of thermal and visual comfort across specific floor areas, the abstracted principles of biology are used to develop building skin tissues. These designs, evaluations, and implementation principles are conceptualised and computationally simulated. The idea of nature as a repository of interconnected dynamic processes that are open to investigation and simulation has changed from a formal metaphor to credible applications that can be implemented to improve the built environment. Environmental catastrophes during the past 20 years have accelerated efforts to gain a deeper understanding of natural systems and processes. A greater congruence between architecture and nature is believed to be possible with the help of applying the principles of natural systems and processes to the construction of buildings. Examining and reflecting on the interrelations of forms, processes, and behaviours can yield useful strategies to develop architectural morphologies that require significant environmental performance enhancements. This paper aims to propose an evolutionary design process with embedded biomimetic principles to generate building skins with morphological characteristics that can be applied in the context of excessive solar radiation e.g. the Persian Gulf region, to maximise thermal comfort by blocking unwanted the solar radiation while simultaneously increasing the visual comfort by increasing the view of the users to the outside.

Keywords:
Architecture; Evolutionary Computation; Biomimicry; Adaptation; Building Skin

1 Introduction

The number of people that are going to live in urban areas is projected to increase by up to 70 % by the year 2050 (United Nations, 2018). The exponential growth of population not only reflects the necessity of having more habitable spaces in the near future but also illustrates an urgent need for a proposal of a design system at which one of its core missions is to inhibit the exhaustion of environmental resources and, at best enhance environmental conditions by lowering greenhouse emission.

Building envelope is one of the most vital design elements that define the interior physical environment, influencing how energy is used in buildings (Yilmaz, 2003). Considering this critical role, in the past few years, many studies and research work around the world have been focused on building envelopes in a bid to improve performance and efficiency with regard to structure, comfort, and energy (Lee, 2004, Selkowitz et al., 2003).

Nature, as a repository of forms and processes, has always been a source of inspiration for solving complex real-world problems across different disciplines. Evolution as a mechanism by which all of these processes and behaviours have been evolved is compelling to be investigated and studied in order to infer a design methodology for problems revolving around adaptation to the environment. According to the biologist John S. Torday, ‘Homeostasis as a scale-free biological process plays an important role in the adaptation of species to their environment throughout their evolutionary developments’ (Torday, 2015).
This paper sets the theoretical context and the background to present a design methodology to address the rising issues of increased energy consumption in areas with extreme solar radiation that are intended to neutralise the impacts of extremely hot climates. It also presents a case study in relation to Al-Bahr tower in Abu Dhabi, UAE, to investigate how biological processes and their connections to the adaptive behaviour of species can lead to extracting useful parameters to be utilised in the early stages of design processes. The study aims to put forward a design methodology which highlights the significance of early design explorations in addressing climatic issues by generating building skins with morphological properties embedded into the shadings and geometrical attributes that enable their adaptation to excessive solar radiation.

2 Literature Review

Nature has always been a source of inspiration in the architecture and design discipline. However, the attention has shifted from formal inspirations to simulating processes. According to Steadman’s key literature (1979 & 2008), “systems and processes inherent in nature can play a key role in driving the architecture closer to harmony to the environment” (Steadman, 1979 & 2008). Homeostatic behaviours explained as species, play a crucial role in their evolutionary adaptation and the emergence of their formal characteristics (Torday, 2015). These processes function in a spatial domain of the internal and external environment with boundaries in between them. The existing measures of regulating these external environmental changes have contributed to the loss of significant amounts of energy through implemented heating and cooling mechanisms (Napier, 2015), among which the cooling systems utilise more energy in summer than heating systems in winter. Cooling systems are being utilised extensively in countries with excessive solar radiation, e.g. the Persian Gulf region, and lead to extreme electricity loads (Attia 2018).

Since the late 20th century, evolutionary multi-objective optimisation techniques have been used extensively as problem-solving tools. The earliest use of evolutionary principles as optimisation procedures can be found in the 1930s work of Sewell Wright (Aedas, 2019). In its simplest form, Erns Mayr defined the evolutionary model as a two-step process: the random variation within a phenotype’s genome and then the selection of the phenotype through environmental factors (Mayr, 1982). The majority of evolutionary algorithms that are currently

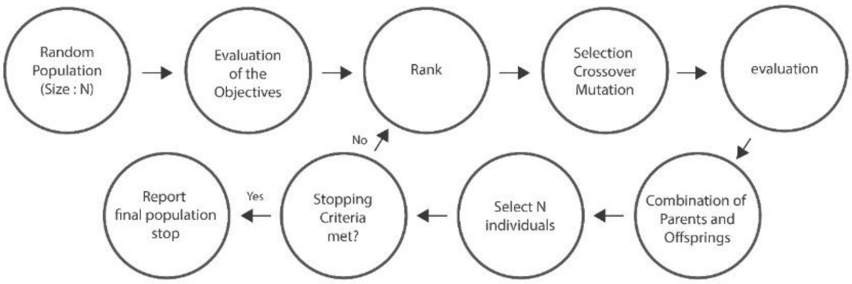

Figure 1 NSAGII algorithm pseudocode.

in use, such NSGA-II (Bateson, 2012), were developed using Mayr's concept. The algorithm starts by generating an initial random population of solutions and then iterates via a primary loop. It continues with alterations of genomes (sets of DNA) via random variations and evaluation of the solutions on their objective performance. A collection of solutions are ultimately chosen using a predetermined selection mechanism. (Turner, 2002) (Figure 1)

In recent years, evolutionary optimisation processes have gained recognition in architecture and design disciplines, both in academia and practice. Research conducted by Ayman Hassaan et al. (2016) investigated the use of evolutionary optimisation in the design phase by exploring geometric formations of the skin at the early stages of design (Mahmoud and Elghazi, 2016). Yun Kyu Yi implemented NSGA 2 algorithm in his investigations of optimising building facades (Yi, 2019).

In nature, homeostasis occurs through evaluations and responsive feedback mechanisms. The application of homeostatic principles for the development of adaptive architectural skins requires an iterative generative model that includes a mechanism of evaluation and reconfiguration of the generated results. Thus, the experiment presented in this research utilises evolutionary computation as the main framework through which generated design solutions address the predefined environmental pressures via an increase in their fitness (Luke, 2011).

2.1 Experiment Setup

In this context, heat received by solar radiation is the parameter for which homeostasis will be maintained and monitored by inserting the secondary evaluation mechanisms as the algorithmic loops into the evolutionary simulation (Figure 2). With a similar goal but a different algorithmic approach to the experiments presented in the paper (Showkatbakhsh and Kaviani, 2020), this paper investigates the application of homeostatic feedback mechanisms into the evolutionary simulations to generate adaptive building skins.

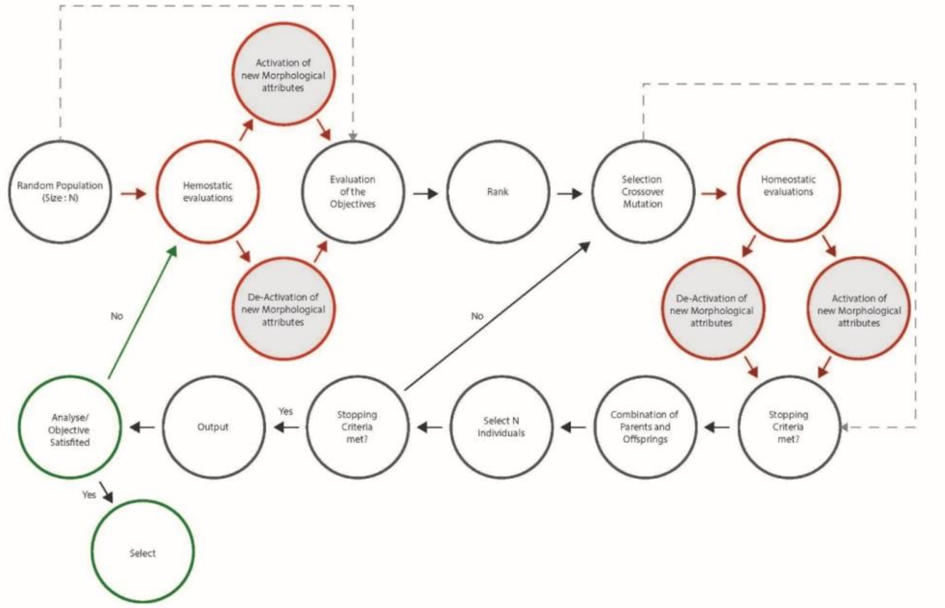

Figure 2 The modified evolutionary simulation workflow with two secondary evaluation mechanisms. The red squares show the modified stages. The green square shows the added step on the application of evolutionary simulation.

The main components of a homeostatic process (set point, receptor and effector) are translated as a secondary evaluation mechanism by which the main evolutionary simulation will be directed towards the emergence of a new set of morphological attributes in the phenotype should evolution favour such properties. Building upon Torday's statement of '*a reference*

point for change' these secondary evaluation mechanisms create a reference point for morphological changes through the evolutionary simulation (Torday, 2015).
The presented experiment utilises multi-objective Non-Dominated Sorting Genetic Algorithm II (NSGAII) developed by Deb. et al. (Deb et al., 2000) as the base algorithm into which the evolutionary simulation is developed. Rhinoceros3D, Grasshopper3D and its plugin 'Wallacei' (Wallacei, 2018) are used to run the simulation and analyse the results thoroughly. In the conducted experiment, 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, see (Makki et al., 2019)).

The design experiment in this research aims to generate building skins with morphological properties embedded into their shadings and geometry that enable their adaptation to excessive solar radiation. Especially in the Persian Gulf Region, which is one of the areas with increasing interest in building constructions while possessing extreme environmental conditions in summer that, in the next decade or so, the temperature can rise up to 60 degrees in summers (Pal and Eltahir, 2016). In the context of this research, the seasonal solstices (21st of June), September, December and March) are considered the date on which solar radiation is calculated and studied. This research, through comparisons to the original skins implemented in Al-Bahr towers located in the UAE, highlights the significance of adaptation of skin to extreme environmental conditions. Secondary evaluation mechanisms have been hardcoded into the evolutionary simulation to steer the evolutionary process in the direction of generating such formal attributes.
In each case study, the original skin of the building will be precisely modelled, and the skin will be exposed to solar radiation on during 21st of June in order to measure the skin performance in terms of the solar radiation occlusion and to provide visibility (view) to the outside. Then, by utilising each case study skin as the basic geometry component, a primitive geometry will be constructed to enable the changes necessary in the simulation.
The experiment will present these behavioural attributes by analysing individual solutions extracted from different generations throughout the simulation.

Table 1 Detailed description of the terminologies used in the simulation

Term	**Short Description**
Genotype	All the genes (and the gene groups) that define a single solution/phenotype. The genotype may be considered as the solution's 'blueprint' or DNA. It is also called genome.
Phenotype	The morphological (or otherwise) representation of the solution. The phenotype is the manifestation of the genotype
Extrusion	The ability that shading morphologies have to extrude out their mass in order to increase the self-shading of the façade and by increasing the surface-to-volume ratio.
Rotation	The ability to move the holes created in cells to maximise the view during the simulation
Offset	The thickness of the sides of each cell of the shadings
Density	The number of cells in a specific area over the surface of the skin

2.1.1 Selection of the Fitness Criteria

The evolutionary simulation was developed to generate a building skin in Abu-Dhabi and Riyadh for the Albahr towers to optimise for the following fitness objectives:

a) *FO1*: To increase the shadow on the buildings by *self-shading* mechanisms (Figure 3)

b) *FO2*: To increase the view from the inside of the buildings towards the outside (Figure 4)

Each of these objectives was formulated to direct the evolutionary simulation toward the emergence of the formal attributes (Table 1 & Figure 6) suitable for the context. Secondary homeostatic mechanisms in the simulation will then steer the simulation towards preferred morphological attributes by creating reference points for change. The architectural application of these fitness objectives, however, holds an equal significance, and they are as follows:

The sample points populate the geometries to calculate the self-shading objective (Pa) efficiently. The volume of the phenotypes is inversely correlated with the number of (Pa). The sun vectors can access some of (Pa), but some are blocked (Ps). Objective 2 is calculated to increase the number of (Ps) in the simulation in order to increase the self-shading on the buildings. The ratio is calculated as the objective since each solution may have a different number of sample points Pa (due to their various volumes).

$$\delta = \sum_{n=0}^{n} P_{an} \qquad \theta = \sum_{n=0}^{n} P_{sn} \qquad FO1 = \left(\frac{\delta}{\theta}\right)$$

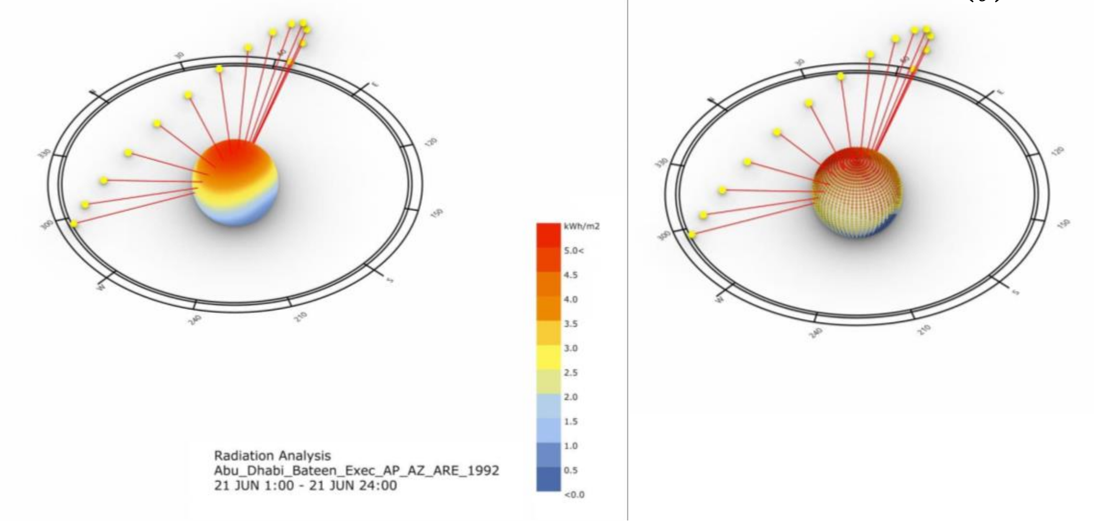

Figure 4 Illustration of sun radiation application over the building

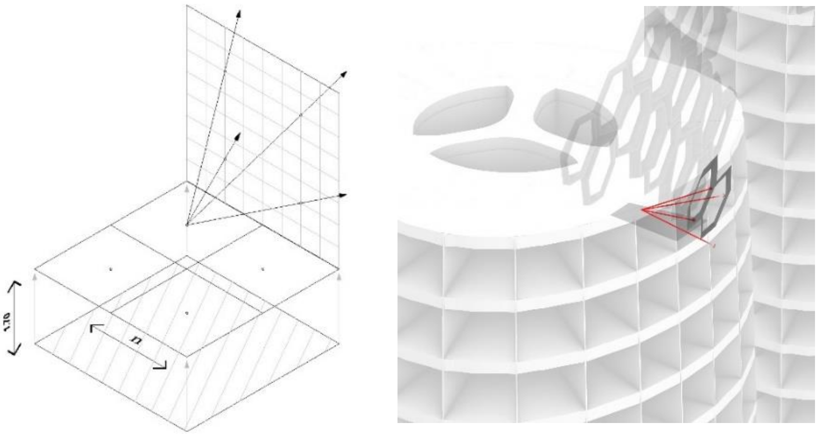

Figure 3 Skin view analysis

Each room on the selected floors (office floors) is divided into four parts, and from each part, vectors are projected to the outside of the building from an elevated point (eye level of 1.7m). The number of vectors that are blocked by the skin will be mapped and shown in percentage to have a clear ratio of blocked and unblocked rays. Vectors (V_a) are drawn outwards, as shown in figure 4. The skin system will block some of them, while some vectors will not hit the skin and pass through (V_p). Fitness objective two is assigned to increase the number of vectors (V_p) from inside to outside.

$$\alpha = \sum_{n=0}^{n} V_{an} \times \mathrm{V} \qquad \beta = \sum_{n=0}^{n} V_{pn} \qquad FO2 = \left(\frac{\alpha}{\beta}\right)$$

Number of vectors (n) = area/x
Number of points to test on window = n
% of view = (β / α)×100
β = Number of blocked Vectors, α = all of the vectors
(Length of blocked vectors < length of vectors)

As a result of the inserted homeostatic mechanisms in the evolutionary system, a new morphological attribute (skin system) will be activated. In order to address the concern regarding the blockage of the view from inside of the buildings towards the outside, the second objective is introduced to the evolutionary simulation to increase the view from inside to outside.

Given the complexity of the design problem, the experiment was limited to 10 (Generation Size) individuals per generation with a total number of 400 generations (in total, 4000 generated solutions). The main purpose of the conducted experiment is to test the success/failure of the implemented homeostatic mechanisms within the evolutionary simulation to generate phenotypes with formal attributes suitable for adaptation to hot climates.

2.1.2 Genotypes and Phenotypes and the development of the skin:

Table 2 Fitness Criteria

Fitness Criteria	**Genes**			
	Offset	Extrusion	Rotation	Density
Increasing Self-Shading	🟦	🟦	🟦	
Maximising the View from Inside to Outside				🟦
	1	2	3	4

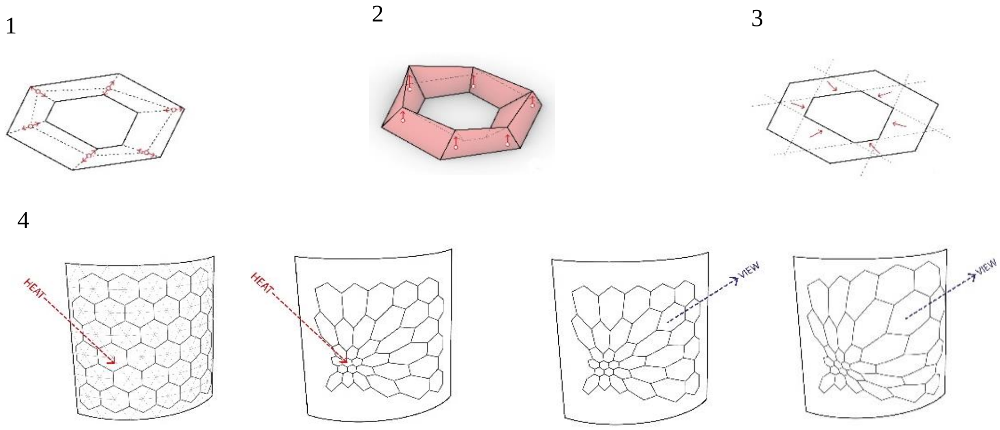

Figure 5 Illustration of an example of genes morphological representation of proposed cellular skin

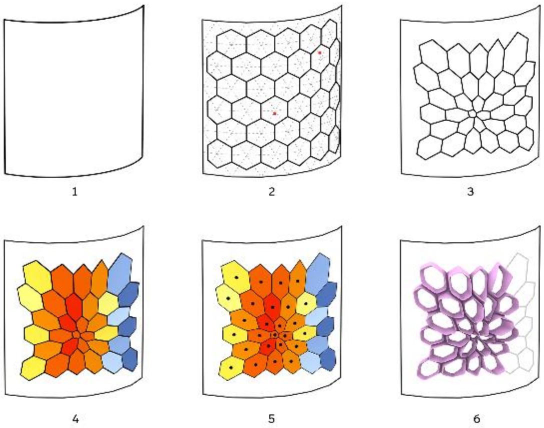

Figure 6 Basic Illustration of the development of each type of skin in the evolutionary design experiment (Cellular Skin with N-gon geometries)

3 Findings and Discussion

In addition to the analysis of the entire simulation for each case study, the best phenotypes were selected among the 4000 phenotypes to study how successful or unsuccessful the simulation was in optimising their objectives and, more importantly, how better or worse they performed relative to the original skin of the buildings in adapting to the excessive solar radiation of the Persian Gulf region. Selecting a set of candidate solutions in the multi-objective evolutionary algorithm while limiting the user's preference is challenging. In order to compare a wide range of solutions with the case studies' original skins, selected solutions are the best option for each of the two fitness objectives. As the visual and the thermal comfort may contradict each other, the selected solution is the relative difference between the best fitness rank of each fitness objective. The fifth one is the solution which addresses the fitness objectives equally. It has the lowest average fitness rank amongst 4000 solutions (for further description of the selection strategies, please refer to (Showkatbakhsh, Kaviani, and Weinstock, 2021; Ladybug Tools, 2019)).

The analysis of each selected solution continues by studying how successful or unsuccessful they performed in the following measurement criteria in comparison to the case studies.

a) What percentage of the building surface area will receive more than the threshold of 3.5 KwH/m2 solar radiation?

b) How much the evolved skin system obstructs the view from the inside to the outside of the buildings?

c) In all case studies and solutions, the only floors selected in terms of function are the office floors.

The selected phenotypes display a wide range of morphological variations. All the selected phenotypes have H-M-A (skin system) activated, while H-M-B (extra skin) was triggered selectively (based on the fitness criteria and solar radiation intensively).

The following pages comprise a series of illustrations of the extended set of selected skin morphologies that evolved in the experiment. The drawings highlight the variations of skin tissues over the case studies. (figures 7, 8, 9 and 10).

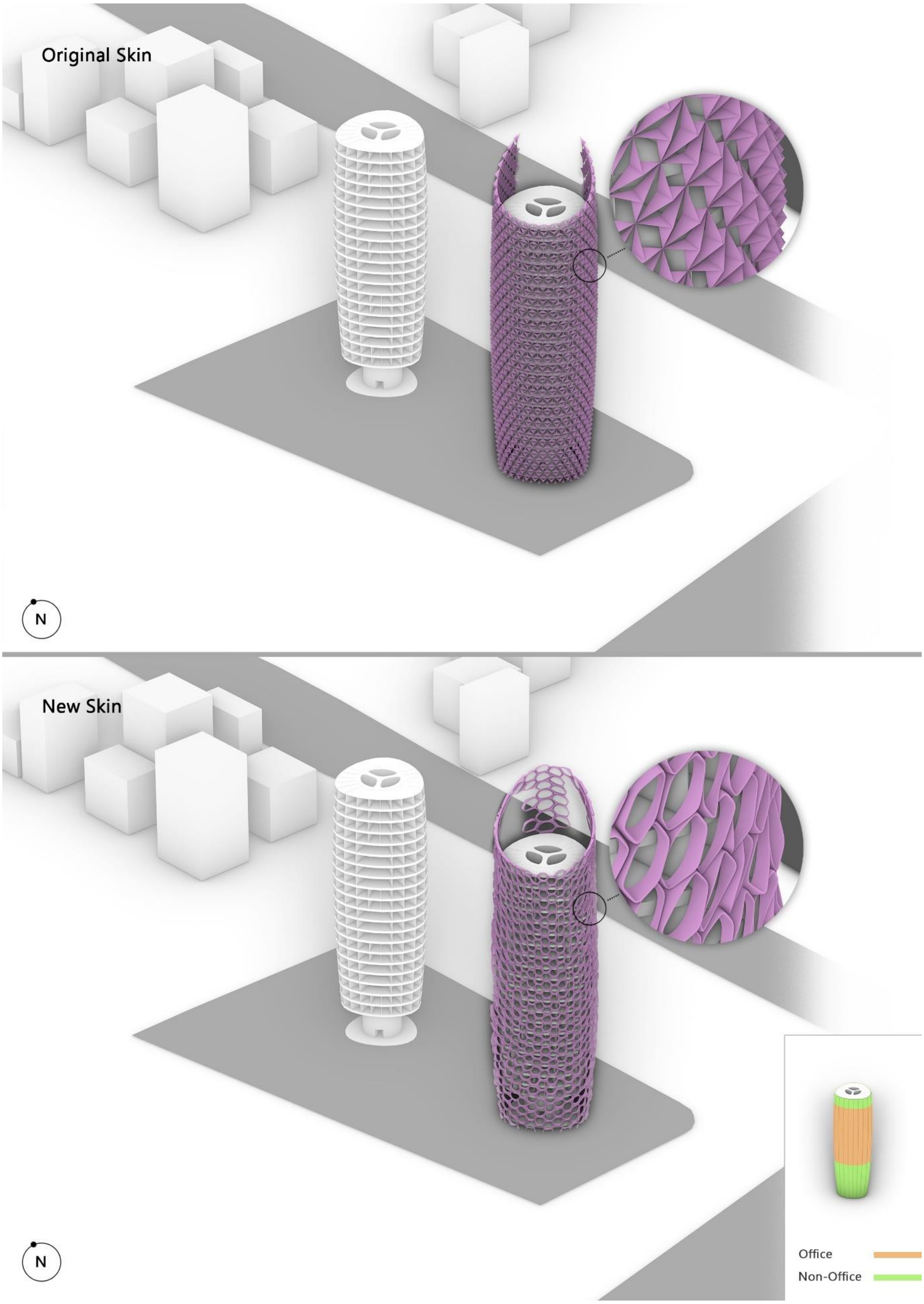

Figure 7 Illustration of Albahr tower before and after applying the biomimetic morphological configuration.

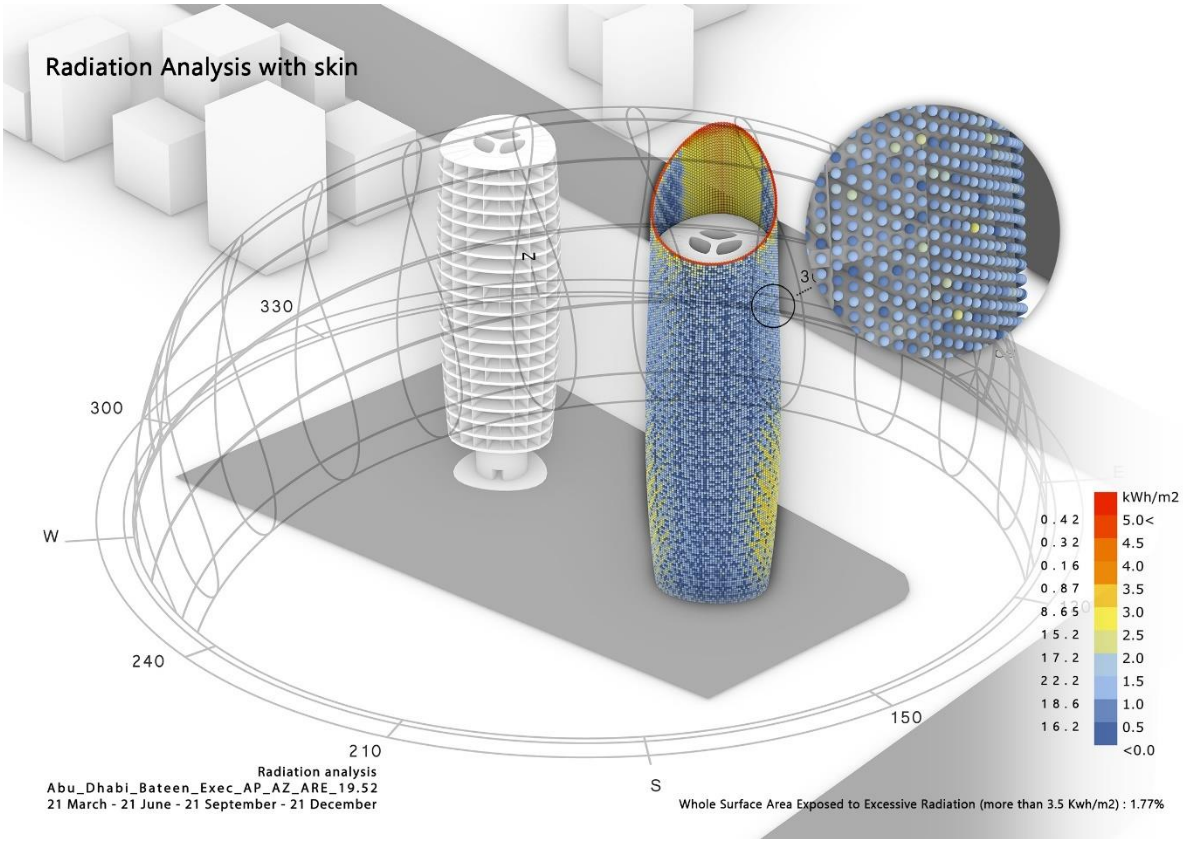

Figure 8 Radiation Analysis of the tower with the original skin

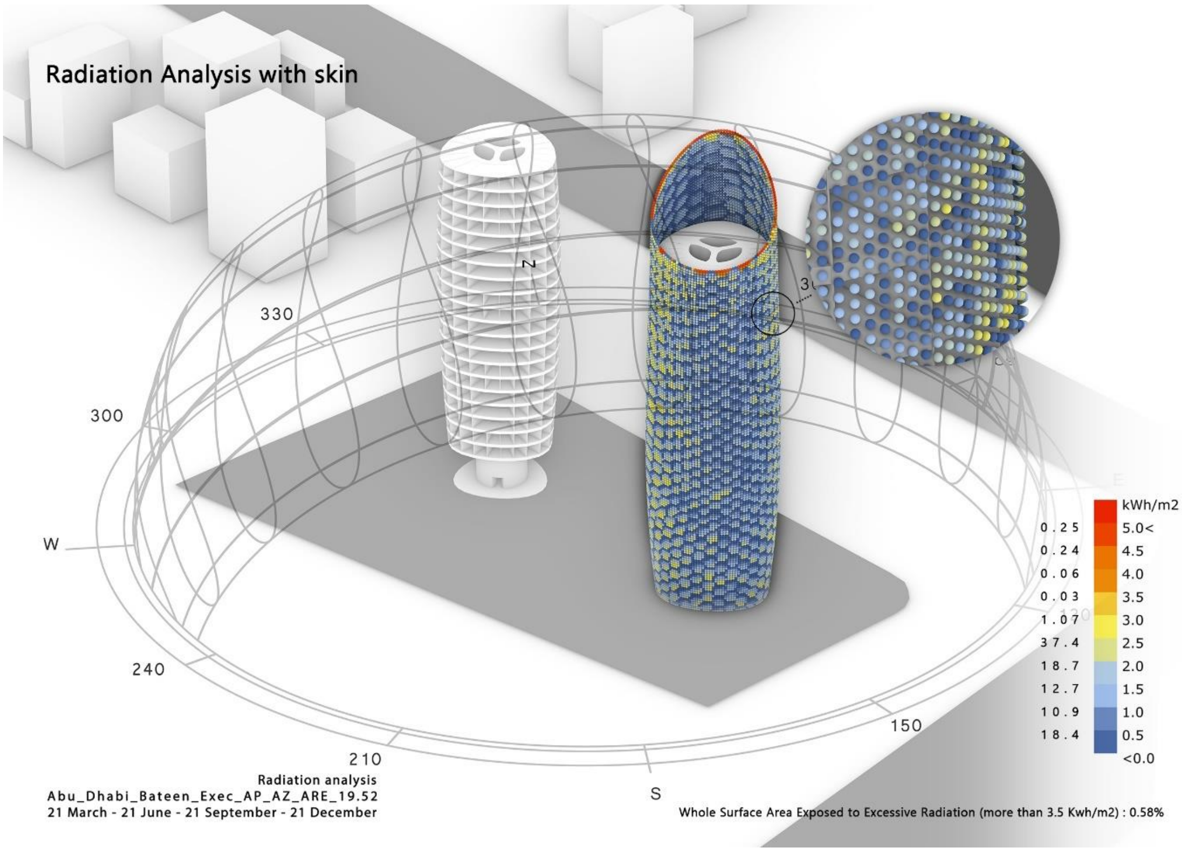

Figure 9 Radiation Analysis of the tower with the new optimised skin (after the simulation)

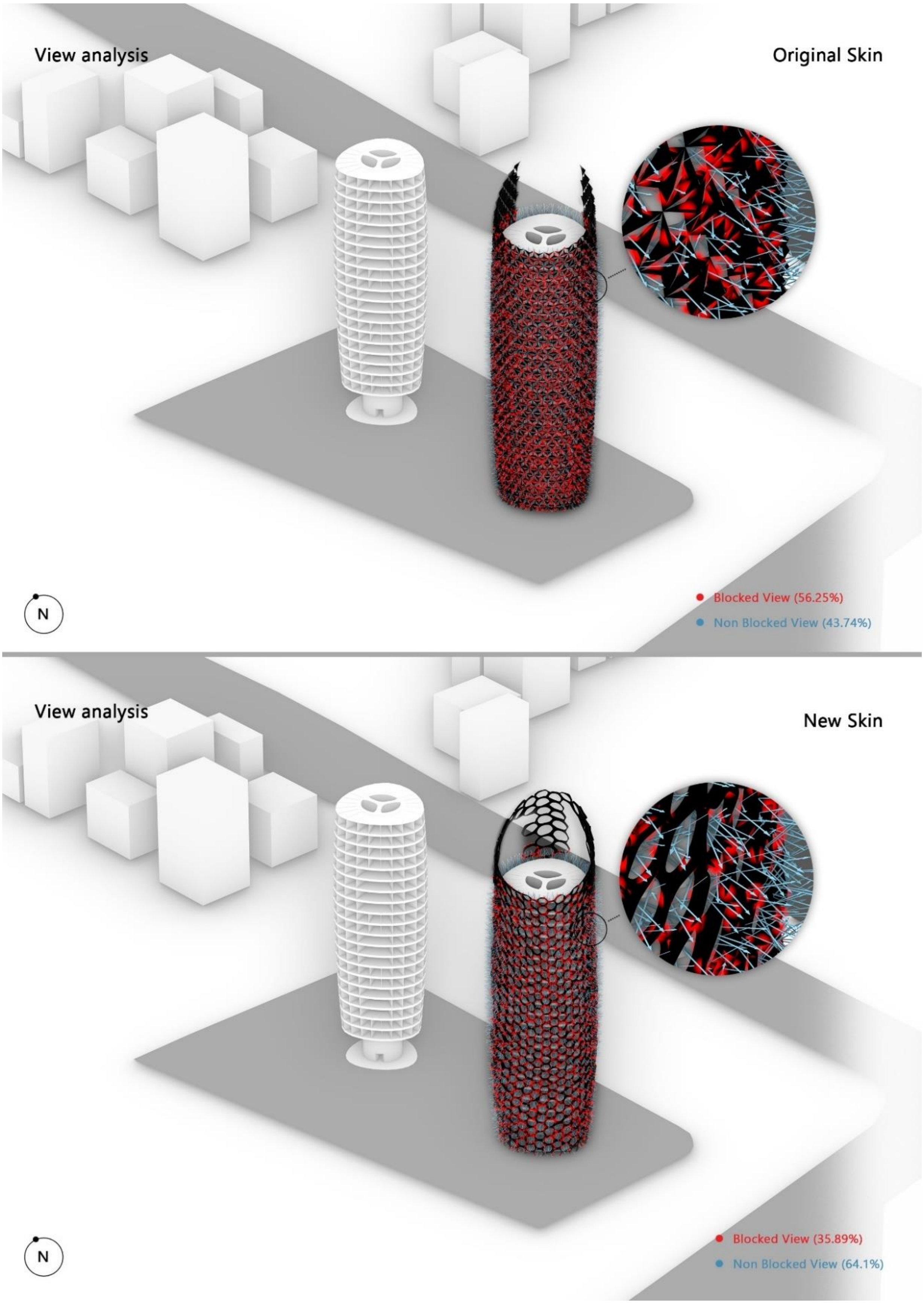

Figure 10 View Analysis of the original and newly optimised skin of the Al-Bahr tower

4 Conclusion and Further Research

This research contributed to two primary fields: building skin design and evolutionary computation through computational experimentation of biologically driven evolutionary design simulations. It highlighted the significance of biomimetic skin morphologies in adaptation of buildings to excessive solar radiation through a variety of changes across the length, width and density of the geometries of the skin. The crucial biological process of homeostasis, which ensures the adaptation of species through their interactions with their local context, was investigated. Through a series of computational experimentations, the abstracted genotypic and phenotypic attributes derived from biological homeostatic mechanisms were applied to a set of evolutionary models to form a novel generative engine that evolves skin morphologies with embedded homeostatic characteristics suitable for their context.

The proposed skin design system of this paper 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. The contribution of the research to the analysis and improvement of visual and thermal comfort in design can be highlighted below.

Thermal comfort: The algorithmic implementation of a homeostatic process's regulatory mechanism to keep the solar radiation variable in a steady state (less than 3.5 kWh/m2) throughout the repeated evolution process. Throughout all selected results of the skin proposals, the amount of solar radiation exposure on the building surface (especially office floors) reduced significantly to below 3.5 kWh/m2.

Visual comfort: As a result of the inserted homeostatic mechanisms in the evolutionary system, a new morphological attribute is activated in the new proposed skin on selected buildings in order to address the concern regarding the blockage of the view from the inside of the building to the outside. This process has been introduced to evolutionary simulation as the second objective to increase the visual comfort of the users.

The main obstacle to this was the computational load required to include these variables within the experiments. The computational setups required for design experiments must be optimised to avoid slow calculations and simulations. Since the intention is to develop a design system to be utilised in a consumer-specification computational platform, the evolutionary design models need to be reformulated to reduce the computational calculations. The materials of the building's skin and the function and specificities of each floor space were considered constant values across all experiments. This was done to ensure the results only reflect the impact of skin morphology on solar radiation intake of office spaces at the selected buildings. The complexity of the solutions and the amount of data produced by the simulations were two disadvantages of adding more factors to the solar radiation analyses. Therefore, another potential path to expand this research is to incorporate variables such as energy flow, room temperature and material studies by developing prototypes and adopting digital twin techniques.

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