Biomimetic Building Skin Development:

Evolutionary Designed Building Skins with Embedded Biomimetic Adaptation Behaviours

Saam Kaviani

https://orcid.org/0000-0001-6551-9565/

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Research-Related Publications

Showkatbakhsh, M. and Kaviani, S. (2020) 'Homeostatic generative design process: Emergence of the adaptive architectural form and skin to excessive solar radiation':, International Journal of Architectural Computing, SAGE Publications UK: London, England [Online]. DOI: 10.1177/1478077120951947 (Download)

Showkatbakhsh, M., Kaviani, S., and Weinstock, M. (2021) 'Evolutionary Design Processes with Embedded Homeostatic Principles - Adaptation of Architectural Form and Skin to Excessive Solar Radiation', *Computer-Aided Design and Applications*, 18(5), pp. 914-953. (Download)

Kaviani, S., Kaluarachchi, Y., Rossi, F. and Ofori, G. (2022) Evolutionary Designed Building Skins with Embedded Biomimetic Adaptation Lessons, in: The 45th Australasian Universities Building Education Association Conference, Western Sydney University: , pp. 664-675. (Download)

Selected Industry Presentations

To ensure the research's contribution to practise as well as to academia, a sample of the methods and workflows developed during this study was presented to the following members of the industry.

LSBU Summer programme events, 2019 & 2018: Research results Presentation
McNeel Europe – Webinar, 2020: food4Rhino webinar series: PedSim
LSBU PGR End of Year (2022) Event, Doctoral Academy Centre, Conference Poster Presentation

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This research is dedicated to my parents, my mother, Roya and my father, Saeid.

Abstract

This study explores the application of biomimicry and adaptation lessons from biology in the design of building skins. Unlike conventional practices that prioritise overall building performance and replicate shading shapes and forms throughout the building skin, this research shifts the focus towards occupants and their comfort. It proposes a methodology that detects and highlights the areas of the building that are most visited by occupants, aiming to enhance the thermal and visual comfort in those specific areas. To achieve this, an innovative approach combining agent-based modelling (ABM) and evolutionary design techniques is proposed. Through computational experiments, the research demonstrates that considering the morphological attributes of building skin forms during the early design exploration phase can improve occupants' view of the outside while blocking unwanted solar radiation. This leads to reduced energy consumption for cooling systems and increased energy performance optimisation.

The study investigates how the biologically inspired morphological attributes of skin tissues affect the thermal and visual comfort levels of buildings, particularly in adapting to excessive solar radiation. It proposes generative and analytical processes to enhance the visual and thermal comfort levels of office floors in selected buildings. The research highlights the importance of biomimetic skin morphologies in adapting buildings to solar radiation and explores the role of biomimicry in the adaptive behaviours and design of building skins. As discussed by Steadman, 1979 in 'The Evolution of Designs: Biological Analogy in Architecture and Applied Arts', the notion of nature as a formal metaphor has evolved into one of a collection of interconnected dynamic processes that are credible applications that can be implemented to improve the built environment.

By applying biomimetic attributes and evolutionary design simulations, the research demonstrates the potential for creating diverse building skin variants with improved adaptive behaviours. The morphological interventions on the original building shadings result in a wide range of morphological configurations that enhance the adaptability of the skin tissues. The study emphasises the significance of morphological variations and adaptation of skin tissues in achieving enhanced thermal and visual comfort for users. The findings highlight the potential of evolutionary design thinking, agent-based modelling, and computational tools to optimise building skins and address environmental challenges such as excessive solar radiation.

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All drawings and figures in this thesis are created by the author, unless otherwise stated.

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Acronyms and Abbreviations

3D – 3 Dimension

ABM – Agent-Based Modelling

AI – Artificial Intelligence

CAD – Computer-Aided Design

CAD/CAM – Computer-Aided Design and Manufacturing

CO2 – Carbon Dioxide

EA – Evolutionary Algorithm

EC – Evolutionary Computation

EP – Evolutionary Programming

ES – Evolutionary Systems

FO – Fitness Objectives

GA – Genetic Algorithm

GP – Genetic Programming

ITKE –Institute of Building Structures and Structural Designs

LCD – Liquid Crystal Devices

PDLC – Polymer Dispersed Liquid Crystals

PV – Photovoltaic

SPDs – Suspended Particle Devices

1 Introduction

By the year 2050, up to 70% more people are anticipated to live in metropolitan regions (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, enhancing environmental conditions by lowering greenhouse emission. Urban expansions in their current shape will leave architects and designers with considerable environmental challenges. The skin of the buildings and, at the larger scale, building morphology must be reconsidered to facilitate their adaptation to unpredictable and extreme environmental conditions.

The current approaches towards adjusting architectural spaces to extreme environmental conditions, such as regions with excessive solar radiations, involve high energy consumption that, in fact, contributes to the sudden climatic changes and global warming in recent decades. The European Council reports that buildings currently consume an estimated 40% of the region's energy and are responsible for up to 36% of the European Union's CO2 emissions (European Union, 2012). In recent years, there has been tremendous development in a growing range of projects concerning building envelope improvements, problems, and opportunities, as well as their influence on building energy demand, because an appropriate architectural design of an envelope may greatly reduce energy use and 'energy consumption reduction' and 'indoor comfort enhancement' are the two most essential aims that must be realised as an outcome of intelligent buildings performance (Selkowitz, 2001). Such energy is predominantly consumed in cooling and heating mechanisms in habitable spaces. (European Union, 2012).

The growth in global populations presents an urgent need to increase the existing habitable buildings. Keeping this fact in mind, it is imperative to develop buildings that offer comfort without adding harm to the world by causing a rise in global temperatures and utilising building resources that will result in a significant amount of CO2 emissions. Building envelope is one of the most vital design elements that define the interior physical environment, therefore, influencing how energy is used in buildings (Yilmaz, 2003). Considering this conclusive role, in the past few years, many studies and research work around the world have been focused on envelopes in a bid to improve performance and efficiency with regard to structure, comfort, and energy. (Lee, 2004) & (Selkowitz et al., 2003)

The emphasis and interest of this research are in biological adaptation lessons are typically sophisticated, extremely reactive, and multi-functional. Therefore, to increase energy performance, a new adaptable architectural envelope is required as opposed to typical mainstream building envelopes that are nonadaptive. Therefore, in contrast to static and traditional building envelopes, a new adaptive architectural envelope is required to enhance energy performance.

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 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 research project, through investigations of homeostatic processes and behaviours of species and their importance in their evolutionary development, aims to address the significance of morphological properties of buildings in their adaptation to contexts with excessive solar radiation.

According to Dobzhansky, the Evolutionary process in which an organism evolves to become more adept at surviving in its environment is an adaptation (Dobzhansky, 2012). Throughout the course of their evolutionary development, living organisms acquire effective strategies for adapting to intense environmental pressures. When confronted with external or intrinsic changes, individual living species and colonies typically retain their stable state. This adaptation propensity is essential for both external and internal changes in species' evolutionary and biological development. The biological process through which individuals and groups maintain a steady state in their surroundings is known as homeostasis, and it is the source of a vast variety of morphological and behavioural features in different species. This fundamental and scale-free biological process, which ensures that natural systems can adapt to their surroundings, manifests itself throughout the evolutionary development of forms, processes, and behaviours (Torday, 2015). Recent discoveries in biology and computer science have made it possible to use the ideas of how species evolve to tackle issues in the real world. In recent decades, the use of random search methods in the architecture and building design disciplines in conjunction with evolutionary multi-objective optimisation strategies has begun to be regarded as a well-established technique for resolving complex problems involving competing objectives (Racimo, 2016).

The area of biomimetics, which has been around for many years and has produced important contributions to the domains of engineering and architecture, has rarely given attention to homeostasis. Otto Schmitt first used the word "biomimetics" in the 1950s to describe the copying of natural models, systems, and principles in order to address challenging human issues (Vincent et al., 2006). In order to apply regulatory systems to the processes of evolutionary design, this project studies interlinkages of processes, behaviours and forms of natural systems that are essential to their

homeostatic behaviours; to provide practical and verifiable regulatory systems that can be incorporated into the processes of evolutionary design.
The goal is to look at how biomimetic adaptation behaviours may be applied inside evolutionary design processes to solve a number of issues with architectural skin that, include adaptability to climatic and ecological challenges. The suggested methodology in this research is tested on various architectural styles, building forms, and geographical situations to create skin tissues with embedded morphological characteristics that significantly improve visual and thermal performance.

In this study, the homeostatic as a biological adaptation behaviour is implemented and studied in the framework of evolutionary design processes. To accomplish this, the section of literature review conducts an investigation into the two key domains of biology and architecture through the use of a number of computational approaches in the methodology chapter on skin design methods; the principles of these two domains are linked. The result of the proposed created generative and analytical procedures is a family of skin tissues with various morphological features that are essential for their adaptation to the shape and location of their building.

1.1 Research Rationale and Identification of Research Questions

This study initially focuses on the concept of transferring living organisms' morphology adaptation and evolution and biological process into sustainable technology for innovation. The research looks at how mimicking some of the recognisable principles and functional characteristics of living species brings suitable functions as well as desired aesthetics to create complete bio-inspired systems for building skins. This study implements machine learning (evolutionary algorithm) that enhances the design of facades of buildings resulting in improvement in the optimisation of responsive and intelligent systems in terms of maximising the visual and thermal comfort of the occupants and reducing excessive solar heat transmission.

Primary Research Question:

1. How can the combination of the strategies from living organisms, biological processes, and computational design principles be used to design a building skin that can bring thermal and visual comfort to the occupants in comparison to conventional ones?

Design-Oriented Research Questions:

2. Is it conceivable to develop a design exploration method for designing building skins as alternatives to conventional mass-produced shadings that have the capability to be modified and applied to different buildings with different shapes and forms?

Biology and Computation-Oriented Research Questions:

3. Can biological lessons and evolutionary algorithms help the design of the skin in order to solve the conflict of view and heat issue of conventional building shadings?
4. Lastly, the study will address the following main question; how can the varying preferences, needs and the location of the occupants in the building, considering their thermal and visual comfort, be addressed during the design process of passive building skins?

1.2 Background of the Study

1.2.1 Building Skin: An Environmental Moderator

A building skin is typically described as an enclosure that separates the inner environment from the outer environment and serves the following purposes: support, control, finish (aesthetics), and service distribution (López, 2017). However, this study focuses on the building envelope as an interface and not as a division between the needs of the inhabitants within and the environmental forces outside.

As a result of the environment's ongoing change, there are always new problems to overcome. The essential environmental concerns that have an impact on a building include light (solar radiation), temperature, relative humidity, rain, wind (air movement), sounds and carbon dioxide (air quality). These problems have a substantial impact on both occupant comfort requirements and building performance. Conventional façades are mainly static, despite the fact that the local climate is a changeable factor; as a result, a significant amount of energy is consumed to regulate inside comfort.

Approximately 60% of the total energy used in buildings is used for space heating and cooling (Omrany, 2016). While exterior climatic parameters can fluctuate significantly, the conventional solutions of a static building envelope and dynamic building services have resulted in a significant amount of energy being lost in ventilating, cooling, and lighting between very well-defined limitations. Consequently, the building industry is accountable for nearly two-thirds of halocarbon releases and 25–33 per cent of black carbon footprint (Ürge-Vorsatz et al., 2012), as well as consuming 23 per cent of the world's primary energy and 30 per cent of the world's electricity (Ürge-Vorsatz et al., 2015).

1.2.2 Design Research Domain

Around 1960, Buckminster Fuller argued for a "design science revolution" based on the idea that political and economical solutions to environmental problems should be prioritised over scientific, technological, and rational approaches (Cross, 2001; Baldwin and Fuller, 1996). Fuller emphasised the significance of the act of design by stating at the beginning of the book that "humanity is moving ever deeper into crisis - a crisis without a precedent" (Fuller, 1982, p. xvii) and at its conclusion that "we have committed ourselves to solving humanity's problem with artefacts" (Fuller, 1982, p. 309). In the book, “The Science of Artificial”, Simon (1996) methodically outlined the science of design. He positioned design as a science among other scientific fields and asserted that design is concerned with how things should be, as opposed to natural science, which is focused on how things are (Simon, 1996). Understanding an artefact's "special properties [that] lie on the thin interface between the natural laws within it and the natural laws without" is necessary for its creation (Simon, 1996, p. 113). Alexander Christopher recognised a crucial distinction between a designer and a scientist; scientists strive to find components of an existing system while designers build components for a new system (Alexander, 1965). In this process, "the ultimate object of design is form" (Alexander, 1965, p. 15), and it cannot be acknowledged without having created a comprehensive grasp of the forces to which the form is emerged. Thompson's concept of form as a "diagram of forces" is reiterated by this multidimensional network of forces, which includes social and physical factors, among others (Thompson, 1992)

The majority of biology's contribution to design has been restricted to the employment of form and shape in the bounds of buildings. However, biomimetic adaptation lessons can influence evolutionary design processes to generate skin morphological attributes that are associated with adaptive characteristics. In this study, these adaptive characteristics are studied in a variety of shapes and forms of building skins situated in extremely hot weather conditions. Adaptive architectural envelopes are defined as those that respond to changing interior and exterior environmental conditions while regulating the internal environment. Adaptive architectural envelopes are able to respond to changes effectively as a result of adaptation mechanisms that anticipate outer environmental changes as well as interior activities and their interactions with occupants (Beesley, 2006).

This study attempts to relate the factors that control species' homeostasis and adaptative behaviours to the elements that control the adaptation of building skin tissues. The application of regulating systems in an evolutionary design procedure is one use of the abstracted principles in the design phase. The other front is the implementation of the extracted adaptation lessons (morphological attributes) in the experiment setup procedure. It requires an evolutionary approach where various levels of assessment, control, and adjustment take place repeatedly. The model should simultaneously take into account internal and external influences. Homeostasis also takes place throughout the evolution of species. Consequently, the chosen design procedure through which the suggested workflow is evaluated is an evolutionary model.

A detailed investigation of the role of biological processes in relation to the species' evolutionary growth is obtained throughout this research to gain the knowledge and abilities required. An understanding of evolutionary adaptation concepts is required to apply such ideas to the computation-based design of building skin. In order to create a workflow of design for this study, it is considered essential to understand how biological fundamentals of evolution are applied via evolutionary computation. Objective evaluations are created in accordance with a series of implementations. This research is positioned within the design field through a series of objective and logical computational experiments that result in a collection of building skin configurations that solve various design issues. It bridges the space in the middle of two fields, architectural (building) design and biology. The findings of this study offer additional information and vision for architectural designers that are curious about how morphological configurations affect the thermal and visual comfort of users within buildings located in extremely hot weather conditions.

1.2.3 Setting the Boundaries of Comfort

In this research, Comfort refers to the ability of a building to satisfy the user's expectations in terms of temperature and visual controls. In architecture, comfort consists of both thermal comfort and visual comfort (Kuhn, Bühler and Platzer, 2001). Figure 1 (below) shows the aspects that facilitate both

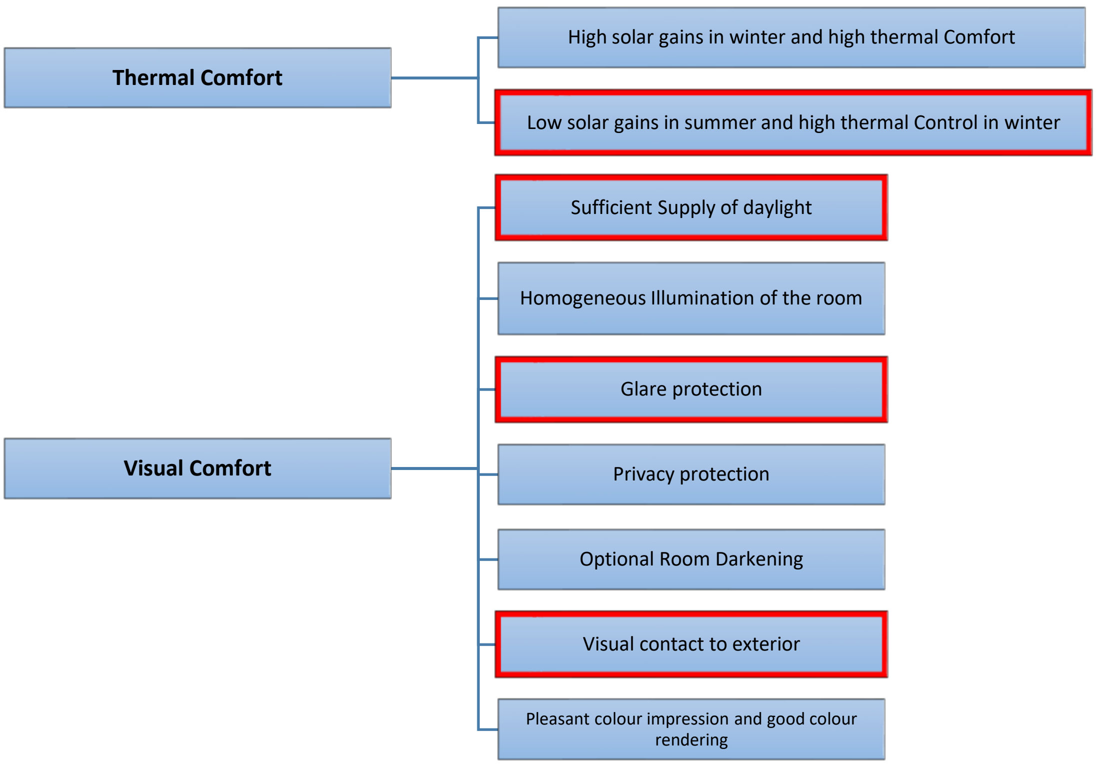


Figure 1 *The Definition and Boundaries of Comfort for This Research (Kuhn, 2001).*

thermal and visual comforts based on the research done by Tilmann Kuhn (2001). Although it may be hard to have a facade that best matches the user's priorities, it is important to concentrate on daylight and the effect that it might have on ventilation and concentration on solar input and the heat produced by it. For most facades, good visual contact with the outside is achieved only with minimised protection against overheating. Moreover, an adequate supply of daylight is achievable only with minimized protection against overheating. It is also possible to minimize winter solar gains when shading systems are applied for glare protection (Kuhn, Bühler and Platzer, 2001). The comfort criteria considered for this study are focused on solar radiation, natural light, and the visual range of the exterior of the building, which is highlighted in figure 1 above.

1.3 Problem Definition

1.3.1 The Global Context

At present, most of the greenhouse gas emissions come from cities that are currently the major consumers of global energy. More importantly, cities' authorities have the capability to do something about climate change by prioritising urban issues in a responsible way over metropolitan areas and buildings. The European Council (EC) reports that buildings currently consume an estimated 40% of the region's energy and are responsible for up to 36% of the European Union's CO_2 emissions. This is shown by plans that are underway to reduce those greenhouse emissions by at least 80-95% under 1990 levels before 2050 (European Commission, Energy Roadmap, 2011). This is evident by looking at how the European Union has been developing and funding numerous building efficiency projects to advance research and innovation programmes, as can be seen in the Horizon 2020 framework (European Commission, Horizon 2020, 2011). The framework recommends raising energy efficiency to a greater level by increasing the coherent utilisation of both passive and active design tactics; in order that heating and cooling loads can be reduced to allow an ascent in equipment energy efficiency and the application of renewable energies (Stevanovic, 2013). Some of the European Union programmes are committed to making retrofitting or setting up energy-efficient technologies, specifically on facades. Superior insulation resources, greener energy supplies, better funding, and more resourceful utilisation of information and communication technology are some of the major avenues being explored (Skou, 2013).

The building envelope divides the interior and exterior environments of a building and is the main barrier that determines the quality and controls the internal conditions regardless of the transient exterior (Sadineni, Srinkath, & Boehm, 2011). Building envelope is one of the most vital design elements that define the interior physical environment, therefore, influencing how energy is used in buildings (Yilmaz, 2003). Considering this significant role, in the past few years, many studies and

research work around the world have been focused on envelopes in a bid to improve performance and efficiency with regard to structure, comfort, and energy (Selkowitz, 2001; Selkowitz, 2003). A proper architectural design of an envelope can meaningfully decrease energy consumption if it makes occupants use fewer cooling systems by controlling excessive heat coming into the building. Additionally, 'the reduction of energy consumption' and 'enhancing indoor comfort' are the central goals that are important to be realised as the standards of smart building performance (Lee, 2004).
The existing measures of regulating external environmental changes have contributed to a significant amount of energy being lost through heating, cooling, or lighting buildings between quite well-known limits. While peripheral ecological factors can change considerably, they can also lead to developing the current solutions of the static building envelope and dynamic building services. Consequently, the building sector is accountable for roughly two-thirds of halocarbon emissions and an estimated 25-33% of black carbon releases (Ürge-Vorsatz, 2012). Additionally, the building sector consumes 23% of the world's primary energy and approximately 30% of the world's electricity (Vorsatz, 2015). Conventionally, the building envelope has been regarded as a thermal blockade or guard that must be; for instance, insulation to stop heat loss or shaded to regulate solar gain. This method limits more effective solutions, where the building envelope is not regarded as a blockade but as a medium. Therefore, traditional solutions for façades and roofs are not planned for prime adaptation to contextual matters and demands. In contrast to buildings, which remain inactive, living organisms respond to the surrounding, and they are able to adjust to the varying weather conditions (Armstrong, 2012). The façade technology in architecture has increased its use of Biomimetic innovations for novel solutions for the purpose of promoting energy efficiency. (Gruber & Gosztony, 2014:8). This project is inspired by biological resolutions to adaptation as they are usually intricate, multifunctional, and exceedingly responsive. Hence, unlike static and traditional building envelopes, a novel adaptable architectural envelope is required for energy performance improvement and the comfort of occupants. The aim of globalising this field of architecture creates the need to explore different facades that are able to improve buildings' heat control quality and the comfort of the occupants.

1.3.2 Study's Target Area - The Persian Gulf

The goal of this research's design experiment is to generate building skins with morphological characteristics integrated into their shadings and geometry that allow them to adjust to excessive solar radiation, particularly in the Persian Gulf Region, which is one of the regions with growing interest in building constructions and has extreme environmental conditions in summer, where temperatures could rise to 60 degrees in the next decade (Pal and Eltahir, 2016). The need to make buildings more comfortable in terms of solar light has led to the growing demand for adaptive facades in the world. Electricity loads of cooling systems commonly used in the Persian Gulf region are outstandingly high. (Attia, 2017). A need for designing and developing a facade that is responsive to both human and environmental conditions is required. A proper adaptive model of an envelope can meaningfully decrease energy consumption (Attia, 2017). Additionally, ‘the decrease of energy intake’ and ‘boosting the interior comfort’ is the central objectives that are important to be realised as the standards of smart building performance. Therefore, there is a need for a new technique in the façade of buildings to reduce the electricity loads of cooling systems, taking into consideration that cooling systems use more energy in summer than heating systems in winter (Napier, 2015). With the facade technology in architecture increasing its use of Biomimetic innovations for novel solutions with the intention of promoting energy efficiency, this research suggests a novel adaptable architectural envelope that can be applied in the Persian Gulf region that is exposed to excessive summer solar radiation in order to decrease the consumption of cooling systems.

1.4 Aims and Objectives

The main aim of this PhD thesis is to explore and demonstrate the benefits of integration of biomimicry and computational design to revolutionise the design of future building facades by implementing machine learning (Evolutionary Algorithm techniques) in order to address environmental challenges such as solar heat transmission control and enhancing occupant comfort in extremely hot climates.
To accomplish the aim of this research, the following objectives have been proposed:

Objectives:

1. To study how biological processes in natural science, specifically living organisms, can give adaptation lessons that are applicable in architecture.
2. To investigate the design strategies of the high-rise building skins in terms of shape, formation, and geometry by applying evolutionary computation and morphogenesis[1] elements adapted from nature to solve the view and heat conflict of the responsive skins.
3. To develop an innovative approach for intelligently considering the local intensity and occupant’s thermal/visual comfort in the design process of high-rise building skins.
4. To develop a design exploration method for generating client-considered skins applicable to high-rise buildings with various shapes and conditions.
5. To develop a building skin design methodology for the improvement of thermal and visual comfort of mass-produced conventional building skins and shadings.

[1] Morphogenesis is a biological process that causes a tissue or organ to develop its shape by controlling the spatial distribution of cells during embryonic development. (McNamara, 2017)

2 Literature Review - Chapter 2

2.1 Establishing the Biomimetic Principal Aspects of the Project

Nature as a solution and inspiration for architecture is a case that has been discussed over ages, arousing interest and constructive discussions (Benyus, 2009). Biomimicry and biomimetics are terms that have a Greek origin. They have derived from the words bios, meaning life and mimesis, which means to imitate. Biomimetics is described as the “abstraction of good design from nature” (Vincent, 2006) or “an emerging discipline that emulates nature's designs and processes to create a healthier, more sustainable planet” (Benyus, 2002). Biomimicry requires humans to mimic design elements in nature and this, in essence, brings about good aesthetics since the architectural forms blend well with nature. Biomimicry involves borrowing from natural elements that experienced, developed, and evolved by nature in the past 3.8 billion years (Pawlyn, 2016). Holistically, this phenomenon explores nature and its contributing characteristics to the world of architecture. The goal here is to meet the ever-changing human needs while simultaneously providing a platform for efficiency and adaptability. This information is valuable in developing future building skin designs that optimise the energy performance of buildings while reducing the adverse impacts on the comfort of occupants.

This research explores how Biomimicry can bring innovation and improvement in mainstream building skin designs and make significant changes to their future. In addition, the study will try to discover the possible benefits of cooperating aspects of computational design into the biomimicry sector, as well as highlighting how it could help make improvements in mainstream skin designs by dealing with environmental issues such as excessive solar radiation, which results in increasing the temperature of the buildings. Moreover, the research investigates how different aspects of natural science, such as evolution, biological processes and adaptation, can be applied and beneficial in the built environment and architecture to come up with innovative designs for building skins while considering the comfort of the people living in buildings located in areas with very hot climates.

2.1.1 Biomimicry as a Design Tool for Thermal Comfort

As previously mentioned, the words biomimicry and biomimetics originate from the Greek words bios, representing life, and mimesis. Biomimetics is explained as the act of using nature to abstract practical designs (Bogatyreva, et al., 2006). It is also an expanding field that imitates designs of nature and processes to develop a better planet that is more sustainable (Benyus, 2002).

Recent developments in technology have ensured that biomimicry can be incorporated into the field of architecture to find lost-lasting solutions to some of the problems affecting the field. One of the notable architects pioneering the utilisation of biomimetic standards in architecture is Michael Pawlyn. He describes biomimicry as the act of studying and mimicking the operational fundamentals of biological mechanisms, forms, procedures, processes, and networks to generate solutions that are sustainable (Pawlyn, 2011). He studies the natural world to establish ways that can be adopted to build more efficient structures and develop systems that will produce zero waste or generate energy for the structures. Biomimetic principles have also been used as the basis of creating new building envelopes in a majority of the research works conducted in the last few years (Lopez et al., 2017). The following examples are three built projects as far as their adaptive envelopes are concerned and how they engage with the surroundings through exchanges of energy and efficiency improvement. The built projects such as Flectofins by ITKE (2012), One Ocean Thematic Pavilion (2012), and a meteorosensitive pavilion known as HygroSkin (Lopez et al., 2017). Plants have inspired the creation of the three structures, and by making them dynamic, the effectiveness of system's reactivity to an environment that is continuously changing will also be increased. The three experimental systems demonstrate biomimicry as a possible tool that can be utilized in the improvement of energy effectiveness in buildings. A culture of dynamic ecological design is created following the effective employment of biomimetics as an instrument in the field of structural design (Gruber, 2010).

Biomimicry is also a representation of substitute methods that can be used in reconciling energy efficiencies with the necessity for high-quality interior environments incorporating flexibility into the design of the envelope, as the doctrine of nature inspires (Loonen, 2015). Present-day building methods provide adequate opportunities that enable the development of inventive adaptive envelopes that are responsive to climate circumstances in a better way, thus enabling the facade to act as a live membrane (John et al., 2005). It is significant to take into consideration that in all scenarios, biomimicry is a concept and a shift of operational principles from biology and not employed to develop the same imitation from nature (Brayer et al., 2013). Biomimetics enables the development of sustainable building systems through the provision of ideas to be discovered and obtained from the designs given by nature. Nature provides significant lessons to be employed as innovative technologies to conduct future envelopes (Vincent, 2001).

Contrary to simply interpreting biomorphic aspects of architecture from biology, the exchange of understanding occurs on a level of performance through the evaluation of strategies in a manner similar to the way problems are resolved in engineering and biology (Kennedy et al., 2015). However, it is not an easy task to transfer from biology to design and technology. Julian Vincent (2006) gives a reflection on the exchange of information between these disciplines and the processes to discover answers to essential questions from engineering and integrate them appropriately with the solutions provided by nature. Potential factors that may contribute to the collapse of transfer may be shallow study, inadequate data from life sciences, inappropriate strategy, or a phenomenon that is not scaleable. Consulting specialists in the field of life sciences may contribute to the success of the transfer (Gruber, 2008). Hence, this new way through which nature inspires techniques to create structures contributes to the emergence of opportunities resulting from the collaborations of biologists inspired by nature and designers (Mazzoleni, 2013).

Evolutionary computation is the preferred technique through which the generative model is created in order to integrate extracted biological principles in skin design processes and to assess and analyse the outcomes. The assessment techniques used to evaluate the outcomes include thermal and view analysis. For this reason, a concise summary of these two fields (computation and biology) is given before the computational experiments in the following sections of chapter two. This study has used computer computational design principles (in the field of computer science) as a bridge between biology and architecture to apply the adapted biological principles and apply them to the design experiment of this research (figure 2).

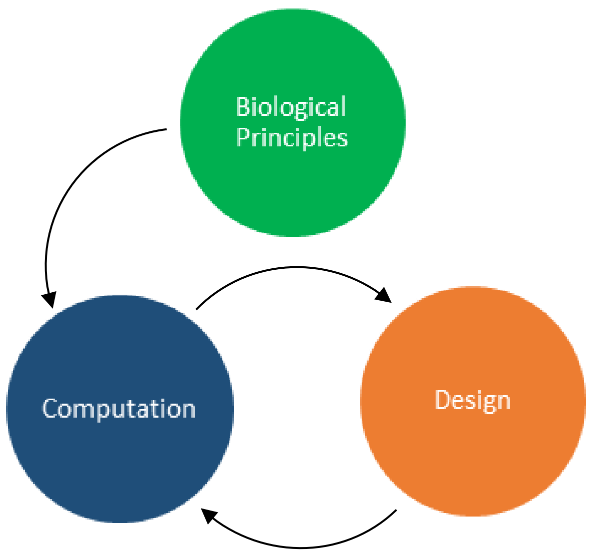


Figure 2 *Computation as a bridge between biology and architectural design*

2.1.2 Adaptation of Biological Concepts in Architectural Discourse

Apart from the built projects previously mentioned in the field of biomimicry, it is worth highlighting the comparison and analysis of other academic research works in this field. There exist some of the most important channels of research that study numerous biological doctrines for innovative strategies to create biomimetic design conceptions in construction envelopes. These research works include "BioSkin" by Susanne Gosztonyi (2010) and Petra Gruber, "Towards the living envelope" by Lidia Badarnah Kadri (2010) and "Architecture follows nature" by Ilaria Mazzoleni (Gosztonyi et al., 2010).

In "BioSkin" (2010), researchers investigate the possibility of biomimetics by discovering pioneering and natural resolutions to create new energy-proficient facades of the future (Gruber and Gosztonyi, 2010). There is the creation of a biological database depending on 240 organic creatures discovered to have capabilities of transmission for envelopes. The created database analyses different role models obtained from nature, inclusive of all types of plants, animals, animal products, cellular walls, or events like swarm activities (Gruber, 2010).

In "Towards the living envelope" (Kadri, 2010), the writer suggests a tactical approach, through practical features and approaches present in nature, for the creation of devise conception for envelopes. This biomimetic design approach is planned to depend on the four significant aspects of the environment: water, air, heat, and light, and design concepts are created from these items (Badarnah, 2012). For instance, a system to harvest water is designed, depending on natural mechanisms to regulate water, like in animals, insect vegetation or human skin, instead of restricting it to certain stratagem or organisms (Badarnah and Kadri, 2014). Another example designed in this research is the heat regulation system, depending on various thermoregulation methods in creatures that minimize the loss of energy for heating and maximize cooling effectiveness through dispersing surplus heat, like termites, tuna fish, and skin of humans or birds (Badarnah et al., 2010).

2.1.2.1 Adaptation

Adaptation is the evolutionary process where an organism improves its ability to survive in its habitat (Dobzhansky, 2012). Another key element in the field of biomimicry is 'Adaptation' which is the natural process by which a living thing becomes more adjusted to living in its habitat. It can also help an animal or plant to survive in the conditions in which they normally live. Based on the 2012 publication of Materials for the Study of Variation (Bateson, 2012), that have been deeply influential in the development of the biological science of evolutionary development and contained the first substantial

account of variation in living forms, “Materials for the study of variation: treated with special regard to discontinuity in the origin of species” (Bateson, 2012). Bateson’s 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” (Bateson, 2012), organized bilaterally or radially in series, and many body parts themselves are also made up of repeated units so that morphological changes or variations occur by changes to the arrangement, number, or the order of parts. There is something here that speaks directly to the principle of adaptation in a new or changing environment in which living beings exist, so 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. (Kaviani *et al.*, 2022)
Many species have adaptively evolved their form and metabolism with other species for mutual benefit. The evolution of specialised morphological features for collecting nectar and pollen, such as the tubular proboscis in flies, moths and butterflies, enable them to collect a rich energy source and, at the same time, enables the transfer of genetic information by pollen grains from the male anther to the female stigma for fertilization (Kaviani *et al.*, 2021). Co-evolution, speciation and adaptive radiation have produced great diversity in the morphology of flowering plants and in the species that act to pollinate them. (Weinstock, 2008) Responsiveness is a reactive behaviour that occurs within the lifetime of the organism. It is comprised of sensing, decision-making, and reactions that are widely distributed in the skin and in the internal organs so that the overall higher-level response of the whole being is the product of multiple local decisions and actions. The responsive movements of plants are most familiar, such as the opening and closing of the petals of flowers in the diurnal cycles of day and night or trees shedding their leaves in autumn as the temperature falls in the approach of winter. Mammals similarly have direct, locally autonomous processes; for example, when one starts to run, the increase in the rate and volume of breath, the opening of pores to regulate the higher internal temperatures generated, and the acceleration of heartbeat are not conscious decisions. (Waddington, 2019).

The combined metabolism of many various individuals and species creates ecological systems. An individual tree's anatomy is set up to support the three-dimensional array of leaves necessary for the metabolism of photosynthetic organisms. It modifies its local environment by the transpiration of water drawn up from the ground, which modifies the structure of the soil, and therefore the water vapour and gases excreted by the leaves modify the temperature, humidity, and oxygen content of the local atmosphere. As a result, this directly influences other plants' metabolism, as will the shade they cast, and produces the environment that bacteria and fungi, insects, birds, and animals inhabit and which they, in turn, modify. (Weinstock, 2008a, p. 27). The flow of energy and material through an ecological system is regulated by the collective responses of the metabolism of all the living forms within it, and over time the regime of natural selection will produce evolutionary adaptions across a range of species in the collective. Over many generations, this has changed the local regime of 'fitness' and, consequently, the dynamics of natural selection. (Darwin, 1872)

2.1.2.2 Inside, Outside, and In-Between

According to Michael Weinstock, metabolic processes in living things are assured by a sequence of changes that take place in interaction with the neighbouring environment (Weinstock, 2008b) (Faraud, 2017). Weinstock states that metabolism is the defining feature in the reciprocal interaction between biological forms and their surrounding environment (Weinstock, 2008b). Homeostasis is a fundamental biological function that maintains metabolism and energy exchange.

Similarly to natural systems, artificial systems convert resource inputs into the energy necessary for living, a process that eventually results in waste in the form of matter of heat (Pataki, 2010; Bettencourt et al., 2007). Using a similar rationale as biology, using homeostasis principles in the design of building skin (behavioural and morphological traits) can have a favourable influence on the energy performance of the buildings.

In biology, an organism's lifespan is determined by the metabolic processes that cause change inside the organism in reaction to its regional environment. (Faraud, 2017).

These metabolic processes guarantee the continuation of life across a range of scales and determine "the relations of individuals and populations of natural forms with their local environment" (Weinstock, 2008). Species have evolved effective morphological characteristics, responsive behaviours, and processes of sustaining the exchange of matter and energy with their environment through the course of evolution. These effluxes and influxes are being monitored, regulated and maintained through responsive regulatory mechanisms, which in turn affects the 'Homeostasis' of an organism (the term that was originally cemented by Cannon (Cannon, 1963)), by which the organism is able to sustain the state of equilibrium through internal and external changes. This equilibrium at any level is defined within three physical domains of any system: inside and outside, and what separates them from one and another, in-between.

Homeostasis amongst all species is manifested through responsive behaviours, morphological characteristics and processes. J. Scott Turner (2016) stresses that homeostasis is not the final result but rather an independent process triggered by unfavourable internal or external changes (L St Hilaire, 2002). Building upon the idea of the process, J. S Torday emphasizes the significance of such processes in the evolutionary development of species which subsequently ensures their adaptation to the ever-changing environmental conditions by providing “reference point for change” (Torday, 2015). This scale-free process (Torday, 2015) by which all biological systems will maintain their vital parameters in an acceptable range has been manifested physically through their formal configuration and morphological characteristics throughout their evolutionary developments.

2.1.2.3 Homeostatic Behaviour

Feedback mechanisms are a crucial component of the homeostatic processes that other disciplines have explored. In response to unanticipated changes, these systems enable organisms to conduct responsive behaviours. The fundamental ideas behind these regulatory processes have a profound influence on other scientific fields and cleared the road for their application in other fields. The fundamental concepts of biological systems' homeostasis and feedback mechanisms served as the foundation for the multidisciplinary field of cybernetics. The thorough investigation of natural system control patterns by D. and K. Stanley Jones (1960) provided insight into the connection between a species' homeostatic mechanisms and its physical architecture (Stanley-Jones, 2014). Norbert Weiner (1985), by connecting the feedback of homeostasis and the biological principles of prediction to constructed machines (artefacts), established the cybernetics school of thought (Wiener, 1948). This connection established a new way of thinking about the artefact and how it relates to its setting. The ability of a machine or artefact to conduct predictive behaviours began to gain footing in the late 20th century. In order to create artefacts that conduct anticipatory behaviours in response to environmental changes, cybernetics investigated the applicability of behavioural principles of governing mechanisms of homeostasis.

Regulatory Behaviours:

Sensing, recognising, and undoing undesirable changes are the three steps of any homeostatic process (Simon, 1996). The variable of concern in this research is a heat-related (solar radiation intensity) factor that is investigated across building surfaces and skin tissues. An iterative model is necessary to carry out these actions continuously in order to incorporate this behaviour into the design process. As a result, the evolutionary model is chosen as the foundation for the research's design trials recognising a change and reversing it. In this study's evolutionary model, two distinct heat and view-related analysis methods are developed to enable the evolution to stop if the variables fall outside of a certain range. Additionally, the evolutionary engine built for this study enables the application of several conditional statements, analysing the differences of the variable of concern throughout various iterative model phases. This is the same as homeostasis' scale-free feature, which applies to various organisational levels in colonies of any kind and to species.

Morphological Characteristics

It has been shown that morphology is just as important to any homeostatic mechanism in both individual species and colonies as regulating behaviours (Simon, 1996). These characteristics may be abstracted and applied into evolutionary models to push the experiments towards developing such morphological attributes in various skin tissues. These morphological characteristics are as follows.

First, morphological configurations can be used to manage the surface-to-volume ratio (figure 5). Increasing the surface-to-volume ratio of a particular volume may help with heat dissipation (described in section 2.1.2.5 and figure 5). This geometrical technique promotes the self-shading processes of the produced morphologies in the design model in addition to modifying the surface-to-volume ratios. One of the most prevalent morphological qualities that promote heat exchange via temperature shifts from one domain to another in colonies and individual species is the ability to shade oneself (figure 6). Moreover, the ability to create groups and partitions over skin tissues as a density strategy can help divide the skin tissues or shadings, based on size and density, into different groups for different functions in order to optimise performance. These geometrical arrangements, Hensel et al. (2004) assert, improve structural capacity, increase strength, and improve flexibility. The development of these morphological qualities in skin tissue that are a manifestation of biological homeostatic behaviours will be explored in chapter four of this research.

2.1.2.4 Homeostatic Principles and their Morphological Manifestations:

The final form and function of a system will depend on how a system responds to environmental changes, according to Gerlee et al. in their study “Evolving Homeostatic Tissue using Genetic Algorithm” (Gerlee et al., 2011). In organisms, homeostasis happens on many different levels and regulates a large range of factors. In the context of this study, heat and visual comfort are two of these factors and the regulatory mechanisms involved with them are being examined.

Any homeostatic mechanism, including thermoregulation, aims to counteract the negative effects of an unfavourable stimulus on the system. These procedures consist of three key components: 1. A set point, 2. Receptors 3. Effectors (Rye et al., 2016). In the event that any deviation is discovered by receptors, effectors will return the system to its set point through responsive feedback loops. Both internal and external stability of the organism is maintained by these feedback loops, which can be either positive or negative. Due to this equilibrium, organisms are able to consistently adapt to changes in their environment that are both extreme and unexpected, yet still, survive. Throughout the course of their evolution, species develop morphological attributes that are actually the conclusion of their homeostatic mechanisms.

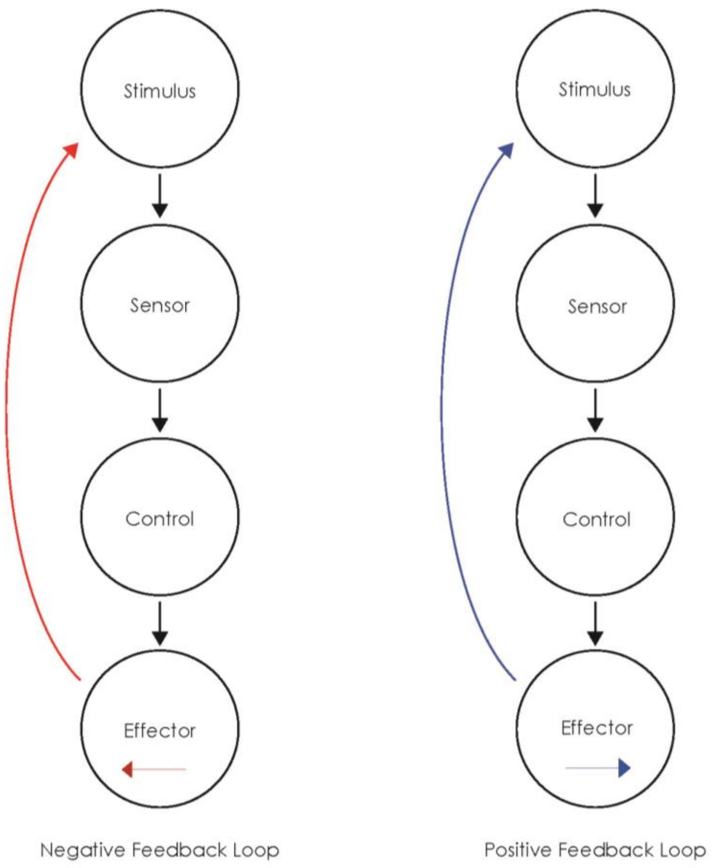


Figure 3 *Feedback loops can be positive or negative. A positive feedback loop recognises a change and amplifies it. A negative feedback loop recognises a change and brings it back to normal. Homeostasis mechanism performs based on negative feedback loop.*

2.1.2.5 The Proposed Mind Map for Extracting Biological Principals

Nature has been for a long time a source of inspiration for architecture, with architects drawing inspiration from nature's morphological processes, skin and form, resulting in responsive environments. Nature is responsive as it is purposeful, complex, predictive and a self-organizing active environment. There is a distinction between sources of explanation and of inspiration. Natural science offers explanations that suggest analogies are valid, whereas a source of inspiration provides imaginative stimulus. The inspiration derived from nature facilitates the mapping process with biological information, which can be incorporated into architectural applications. This process results in the creation of a responsive environment described as a self-organising, active and purposeful environment.

The information applied in the collection of data was obtained from an initial study in attempts that were made to understand the evolving process of the Geranium stem and extract how it could be manipulated for an architectural application as a partitioning principle for architectural skin modules while at the same time how it can help to design responsive skins for buildings to control the excessive solar radiation. In order to classify the data collected from nature and how they could be applied to architecture, the mind map table below has been introduced. The goal of this mind map is to find suitable natural adaptability and response of living organisms to their environmental conditions and to find out how the responses and adaptability can be applied in architecture when the context is the same.

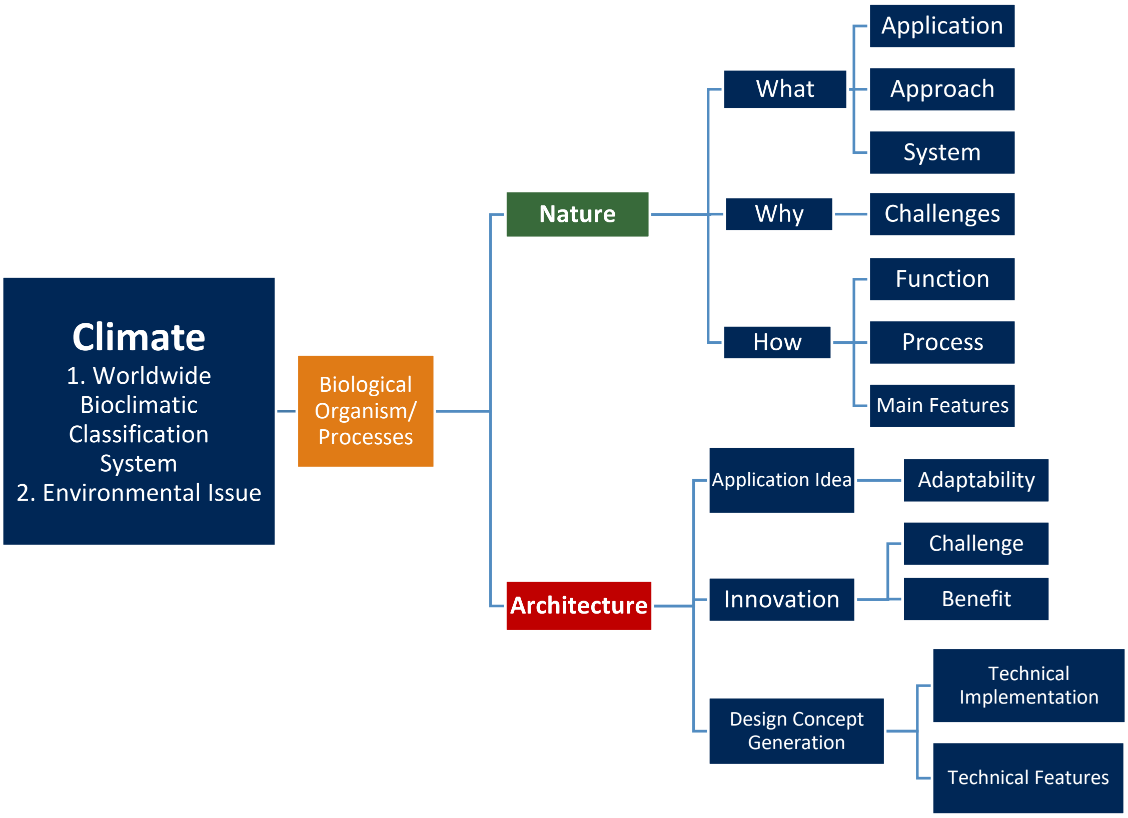
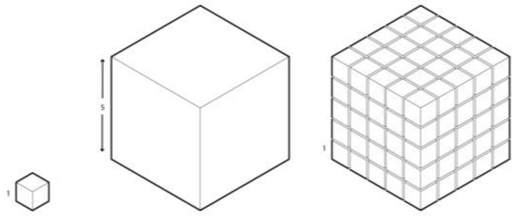


Figure 4 *The way the proposed data mining mind map has been set-up for this research*

The Biological lessons chosen for this research project that has been extracted from the mind map are the following. (the following living organisms have been analysed and in the complete version of the mind map available at: https://www.mindmeister.com/966873314?t=PXf65DicQ6)

- **Jackrabbit: Surface-to-volume ratio [2]**

The ear of jackrabbits is approximated to be 19 per cent of their bodies. The huge ears of the Jack Rabbit give a vast area of exposed skin that is densely packed with blood veins. The blood vessels in the outer part of the rabbit's ears widen when the surrounding air temperature is slightly lower than the rabbit's body temperature, as example when it retreats from the hot desert sun into the shade. This lowers the rabbit's body temperature by increasing the surface-area-to-volume ratio of the vessels, which favours heat loss to the surrounding air (Weebly, 2022).



Total surface area (height x width x number of sides x number of boxes)	6	150	750
Total volume (height x width x length x number of boxes)	1	125	125
Surface-to-volume ratio (surface area / volume)	6	1.2	6

Figure 5 *Left side: Jackrabbit with huge ears to maximise surface-to-volume ratio (Weebly, 2022). Right side: Author's illustration of geometrical attributes extracted from Jackrabbit's morphological quality which can be applied in architecture*

- **Ribbed Cacti: Self-Shading Attribute**

The Barrel cacti shape and ribs can provide self-shading and enhance heat dissipation. Cacti use self-shading as one of their key adaptation strategies. Through its unique rib structure, the cactus stem expands, shrinks, and maintains a high surface-to-volume ratio. According to studies, Cacti Grusonii may extend up to 54% of its original surface area (Bhushan, 2009). Self-shaded regions in between the ribs assist in decreasing the surface temperatures when the ribs are shrunk. As the cactus becomes larger, the surface-to-volume ratio rises, allowing heat and light to escape. At the cortex, there are areoles from which spines develop, self-shading and generating a colder environment. Through these morphological modifications, Cacti may attain a temperature differential of up to 17°C in winter and 25°C in summer between the surface and air temperatures, according to studies. Kuru et al. (Kuru et al., 2020)

[2] In surface area to volume ratio (SA:Vol) the outside surface area of an object to its internal volume is compared has a direct relationship with heat loss.

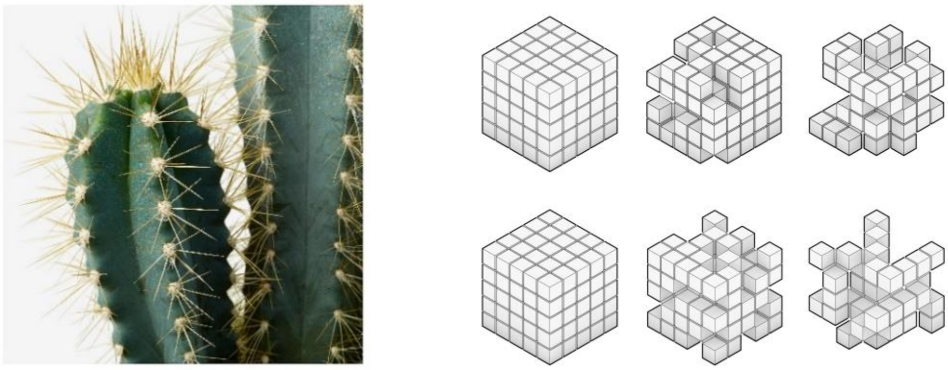


__Figure 6__ Left side: Ribbed Cacti with Self-Shading Attribute (Bhushan, 2009). Right side: Author's illustration of geometrical attributes extracted from Cacti's self-shading morphological quality which can be applied in architecture

- **Homeostasis Principles**

Homeostasis refers to the biological processes through which organisms and collectives keep a regulatory behaviour in their environments, and encompasses a wide range of morphological and behavioural properties shared by many species. Homeostasis and evolutionary developmental processes control these morphological traits. Examining and reflecting on the interrelationships of forms, processes, and behaviours might lead to effective strategies for computational skin design methodologies that demand significant environmental performance improvements. (Turner, 2002, p. 192).

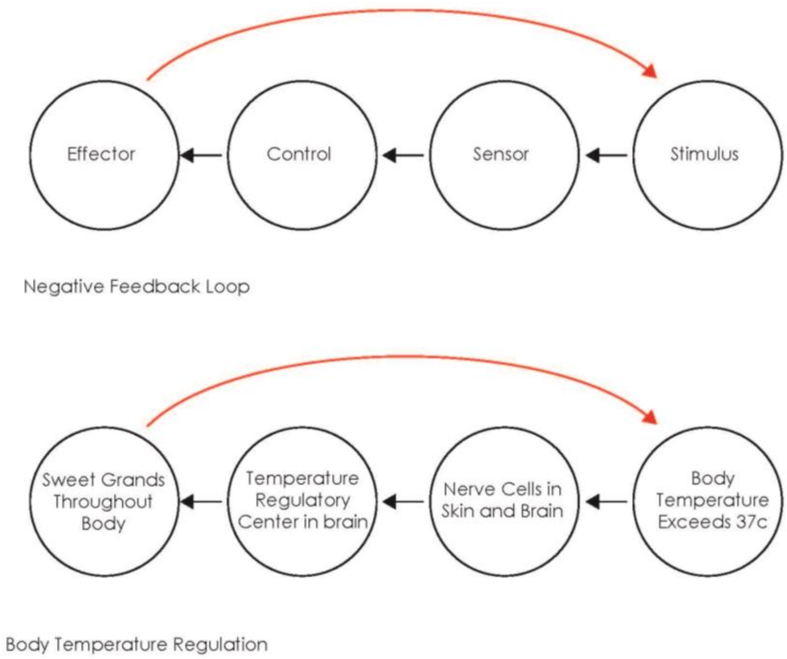


Figure 7 Body *temperature* regulation as a homeostasis mechanism

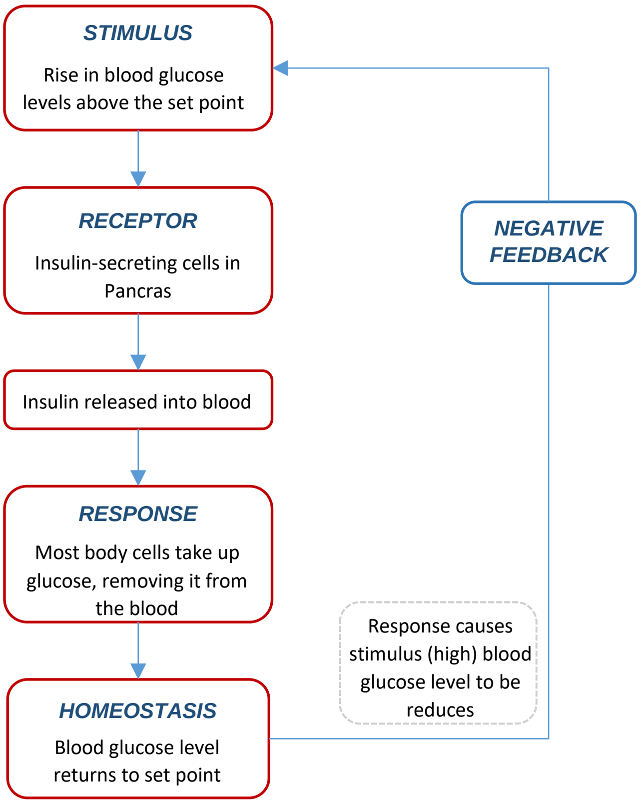


Figure 8 *Negative Feedback Loop of blood glucose homeostasis mechanism*

According to Torday, it is essential to simultaneously study an organism's biological internal development and changes (ontogenetic) and the evolution and external changes (phylogenetic background) in order to adequately appreciate evolution's mechanism and its influence on species' attributes and morphology (J. Torday, 2015). Every stage of evolutionary adaptation and biological development involves the biological process of homeostasis, which is essential to life. Therefore, it must be examined from both angles. Any system, whether biological or synthetic, must be able to develop adaptation to possible unanticipated changes in its environment over a wide variety of time scales in order to survive. Rather than creating artefacts based on hypothetical predictions, Herbert Simon (1996) postulated that implementing regulatory processes was a more practical way to create environmental adaptation. He stated that two procedures—"homeostatic mechanisms that make the system relatively insensitive to the environment and retrospective feedback adjustment to the environment's variation" (Simon, 1996, p. 149)— are more beneficial in the adaptation process than predictive behaviours.

The phrase "Milieu Interieur" was first used by Claude Bernard in the late 19th century to describe "the stability of the internal environment" (Bernard, 1974). He asserts that it is a necessary condition for any biological organism to be able to live a free and independent life (Bernard, 1974). Bernard believed that interstitial fluid surrounds the internal organs and tissues of multicellular organisms, maintaining their stability through changes in the external environment. The central idea behind Walter Bradford Cannon's coining of the term "homeostasis" later in the early 20th century was Bernard's research (Cannon, 1963). The process by which a biological organism maintains its steady state is known as homeostasis (Martin, 2008). Eventually, this stability will lead to the "maintenance of life and evolution" (Novak, 1968, p. 99). Numerous variables, each under the control of a homeostatic process, must be maintained in order to sustain the internal state of a biological system at a steady state. Homeostasis, according to Cannon, is a highly organised process that results from the organism's self-governance (Cannon, 1963). This characteristic is essential for a system's context responsiveness and, on a bigger scale, its evolutionary adaptation. Temperature and glucose level regulating mechanisms are two examples of homeostasis.

- **The Geranium plant stem cells: cell grouping and partitioning technique**

Hensel et al. (2004) discuss the example of the geranium plant, suggesting that it is “the perfect example of integration and differentiation in a plant stem.”

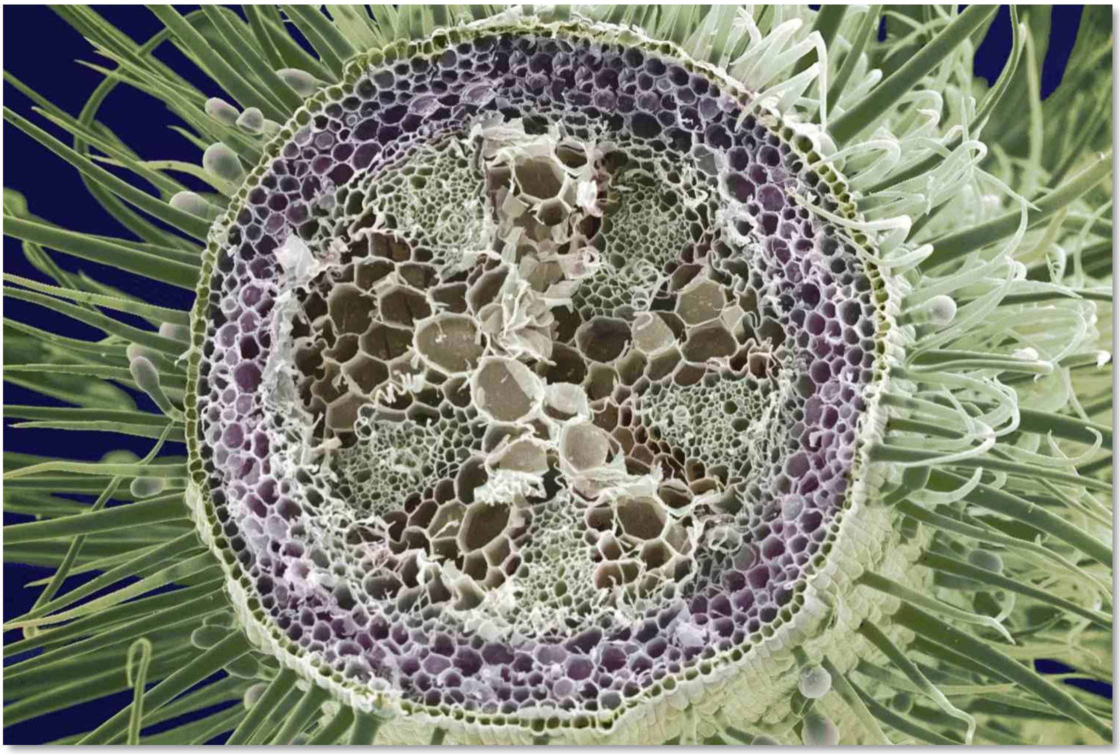


Figure 9 *Cross-section view of the geranium plant's stem (Hensel et al., 2004)*

As shown in Figure 9, the stem is made up of specialised cells and differentiated vessels, which are arranged as closely packed bundles. This geometrical arrangement, Hensel et al. (2004) asserts, improves structural capacity, increases strength, and improves flexibility. According to Hensel and his colleagues, every cell plays an essential role in creating structural capacity. For example, the xylem vessels (represented in figure 10) are primarily designed to transport nutrients and water from the roots. Due to their critical role, these cells are helices of lignin which ensures that elongation does not affect the plant's stability. Similarly, the phloem cells (represented as five bundles of green vessels) form part of the vascular system that distributes hormones and carbohydrate cells. Hensel et al. (2004) also explain how the stem achieves movement, stating that the parenchyma cells take in water to increase their size and vice versa, movements that cause deformation and helps the plant to move around objects. To constrain the plant in a specific direction, the stem cells are all different sizes and oriented differently. To sum up, the geranium stem has influenced this study with three important lessons; density strategy, minimum usage of the material for perimeter and partitioning of the cells for different functions and cell growth processes.

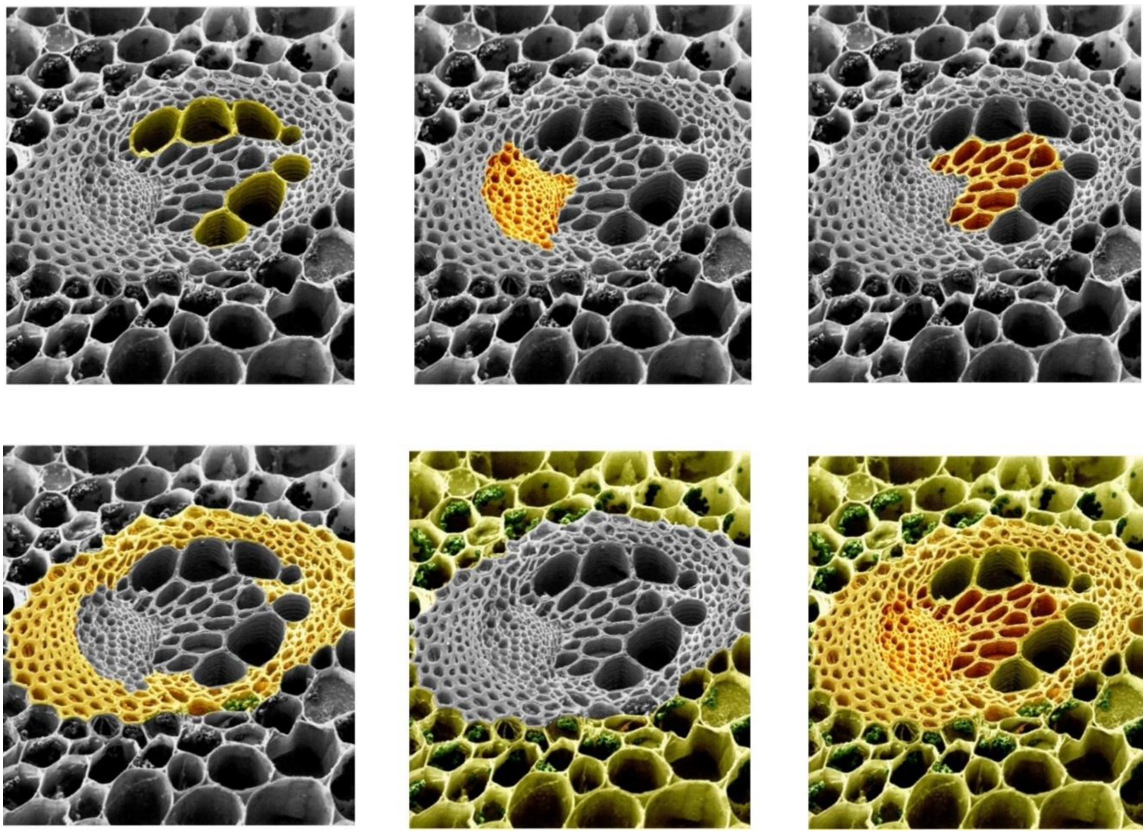


Figure 10 *Cross-section view of the geranium plant's stem that follows the same principles of cell grouping as Geranium Plant showing different groups of cells with different functions (Hensel et al., 2004)*

2.1.2.6 Relevance in Design:

Architecture and design have always drawn inspiration from nature. However, the focus has shifted to simulating processes rather than formal inspirations. Systems and processes found in nature can play a significant role in bringing architecture closer to harmony with the environment, as is evident in the differences between the revised and original editions of Steadman's (1979) book "The Evolution of Designs: Biological Analogy in Architecture and Applied Arts" (Steadman, 2008). The evolution of a species' homeostatic behaviours and the emergence of its formal characteristics depend heavily on these behaviours. These processes operate within a spatial domain that includes the internal environment, external environment, and boundaries in between.

Evolutionary design processes have been used as a robust problem-solving mechanism in architecture and design in recent years, given the importance of the homeostatic behaviours of species within their evolutionary development (Torday, 2015). The homeostatic behaviours of species within their evolutionary development are important as feedback mechanisms and algorithmic loops in the evolutionary design processes to drive the simulation to generate solutions with morphological characteristics that enable their adaptation to extreme environmental conditions. The skin, which in fact, is inseparable from the overall morphology of an organism, is a key player in controlling the exchange of energy and matter between the inside and outside environment. Architectural forms and skins, in a similar fashion, are situated between internal environments where human activities occur in 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 (Gruber and Gosztonyi, 2010). These exchanges are enabled by processes and unique formal characteristics. Likewise, architectural forms and skins can be evolved in a way which contains formal characteristics suitable for their environments.

Conventional cooling and heating mechanisms use up to 60% of the entire energy in the buildings (Omrany et al., 2016). Given the significance of the morphological characteristics of species in their adaptation to extreme environmental conditions, this research aims to develop a method for creating skins produced by the proposed mindmap and an evolutionary design system within which the biomimetic morphology of the building skin contributes to their adaptation to the contexts with excessive solar radiation.

2.1.3 Evolution

The Cambridge dictionary defines the term evolution as “a gradual process of change and development.” In biology, the term evolution is defined as “the process by which the physical characteristics of types of creatures change over time, new types of creatures develop, and others disappear.” (Cambridge English Dictionary", 2019) Evolution is caused by changes in gene expression as they are passed through the hereditary process from mother to offspring. Natural processes, including genetic drift and natural selection, are responsible for triggering changes in gene expression. This assertion is supported by scientists and researchers who provide evidence to show the role of natural selection in evolution. The current literature describes natural selection as the process of "differential survival and reproduction of individuals in populations" (Colautti, & Lau, 2015). It occurs when parents pass on modified genes to their offspring resulting in differences in characteristics and traits of the new generation.

The theory of evolution by natural selection was introduced by Charles Darwin and Alfred Russel Wallace independently in the middle of the 19th century. In 1858, they jointly presented their concepts at the Linnean Society of London (Darwin and Wallace, 1858; Wallace, 1858). Within a year of their joint discovery, Darwin published his influential book "On the Origin of Species," in which he outlined the concept of evolution by natural selection in great detail (Darwin, 1859). The foundation for modern evolutionary theory has been laid by Charles Darwin's theory of evolution, which argues that natural selection can modify descent through time. He believed that population growth would lead to competition between individuals with the best combinations of morphological and behavioural traits, which would result in the survival of the fittest individuals at the expense of the rest. Scientists today still consider this theory as one of the key sensible explanations for evolutionary changes. Natural selection explains how living organisms maximise their biological fitness as a result of living in harsh environments or due to developmental and genetic factors. It is important to note that Evolution in animals is a bottom-up process on the basis that organisms evolve their form in response to external changes in the environment instead of changing to fit a predefined form. From a digital perspective, these environmental changes are comparable to external constraints on design systems. In architecture, these may include weather constraints, occupancy and the site.

The process of evolution occurs systematically "from heredity to genotype[3] to environment to variation to phenotype[4]." (Campbell, 2019) Imposing the environment eliminates the likelihood of passing on undesirable features. Although Darwin's conception of evolution is simply referred to as Darwin's theory, it encompasses a number of theories to explain concepts such as natural selection and Darwin's vibrational evolution. In simple terms, Darwin's theory of evolution can be summed by the idea that variable essences are an essential feature of the living world. Darwin's proposal challenged the traditional way of thinking, which held that the natural world is made of invariable essences. Furthermore, Darwin's theory suggests that the change in evolution underlies the changes witnessed in organisms' populations from one generation to another (Darwin, 1859).

[3] A Genotype is an organism's set of heritable genes that can be passed down from parents to offspring (Campbell, 2019).

[4] Phenotype (from Greek pheno- 'showing', and type 'type') is the term used in genetics for the composite observable characteristics or traits of an organism (Campbell, 2019).

2.1.3.1 Evolutionary Design

Evolutionary designs are founded on concepts derived from evolutionary biology, computer science, and design. Moreover, this design technique uses concepts from natural selection, and it also integrates analysis software with CAD (Bentley, 1999). Evolutionary design has been applied in various forms over the past decade. For example, it is used to optimise the functionality of smart buildings, plays an important part in the design of aesthetic and 3D artistic forms (Tabuada, et al., 1998), and finds application in the creation of artificial life (Paun,1995). Regarding architecture, evolutionary systems entail the use of evolutionary algorithms to improve the performance of buildings as per the changes in natural phenomena and varying human needs (Bentley, 1999).

The idea of Evolutionary Algorithms (EA) has been defined as a “heuristic-based approach to solving problems that cannot be easily solved in polynomial time, such as classically NP-Hard problems, and anything else that would take far too long to exhaustively process.” (Soni, 2018)

Just like Darwin’s theory, EAs are founded on the principles of natural selection. More specifically, EA is divided into four stages.

- Initialization
- Selection
- Genetic Operators
- Termination

EA designs are based on the principles of biological evolution, including selection, reproduction, recombination, mutation, and random sampling. Given a quality element, an evolutionary algorithm evaluates candidates and tries to find the best solution. The primary benefit of using EA is the flexibility it offers because most EAs work perfectly well in multiple complex scenarios. Randomness ensures that the quality function is maximized to fit the problem domain (Hart et al., 2005). New generations are made up of components that are fitter than old ones. Recombination (represented by binary operators) and mutation facilitate this. Recombination can be used to evaluate multiple candidates in a bid to produce the fittest offspring (Goldberg, 1995; Rudolph, 1998). This is unlike mutation, which is used on a single candidate to produce one offspring. The whole process is iterative, meaning that it goes on until the best candidate is generated.

2.1.3.2 Evolutionary Computation

Evolutionary computation is a concept that leverages the evolution theory to optimize methodologies and computer-based processes. Scientists usually use the term evolutionary computation as a general term that encompasses evolutionary-inspired problem-solving strategies (Bäck, Fogel, & Michalewicz, 2018). EC is applied not only in architecture but also in other industries that rely on prediction algorithms and accurate analytics. One of the key subclasses of Evolutionary computation is Evolutionary Algorithms (EA) which are also classified under stochastic search algorithms. EA works on populations using Metaheuristics optimization techniques. Essentially, the concept of Metaheuristics refers to higher-level procedures that are designed to locate, produce or partial searches based on heuristics or lower-level procedures. EA is applied to solve a myriad of optimisation problems, including Dynamic programming, Evolutionarily related issues, Calculus-Based Techniques, Annealing Evolutionary Algorithms, Guided Random Search Techniques, Enumerative techniques etc. (Menges, 2011).

Recent advancements in computational design suggest that this technology offers remarkable benefits in fields such as architecture on the basis that it facilitates the design of smart buildings to fit various design requirements (Mosleh, Dalili, & Heydari, 2018; Wong et al., 2005). Evidence of this assertion can be found in some of the newest generative software such as Autodesk's architectural software, which has the capability to produce automatically custom designs. Such software allows designers to input customized commands that produce a multitude of unique designs as per the design requirements (budget, constructability, environmental conditions, and performance dynamics).
Undoubtedly, computational designs offer a myriad of advantages, as evidenced by the numerous practical applications mentioned here. However, there are inherent limitations that come with the use of computational designs. For example, there are suggestions that computational designs could corrupt the architectural field akin to other industries where automation has completely revolutionized traditional techniques. The effect in this regard is that the new technologies may affect the livelihood of architectures, which are traditionally heavily involved in the design process in terms of deciding elements such as interior design, aesthetics, and style.

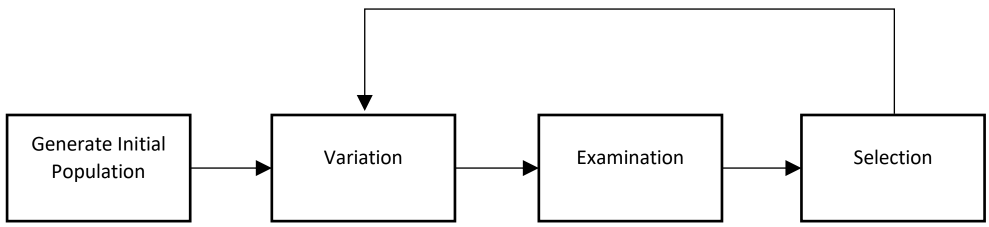


Figure 11 *The evolutionary process in generation in computation*

2.1.3.3 Evolutionary Systems

This study has used computer science principles in order to apply the adapted biological principles of this research to the architecture and design sector. The science of Evolutionary systems is concerned with exploring the consequences of changing the interaction through evolution by natural selection. Specialists in this field combine experimenting with population genetics and mathematical models to determine the relationships between the elements (Richards et al., 2018). Evolutionary systems are designed in a manner that mimics the process of evolution as described by Darwin's evolution theory. This concept can be applied to enhance design creativity to produce smart systems (Hensel et al., 2004).

Evolutionary system function is powered by the evolutionary algorithm. Some of the common evolutionary algorithms include:

- Genetic Programming (GP)
- Genetic Algorithm (GA)
- Evolutionary Programming (EP)
- Evolutionary Strategies (ES)

While all the above techniques have been tested, GP and GA are the most popular ones (Menges, 2011).

In essence, Evolutionary systems trigger creativity and provide solutions that would otherwise be challenging to find. For example, the fact that evolutionary systems allow for human interaction means that designers can easily come up with designs that meet specific aesthetic characteristics. Moreover, knowledge-lean component-based representations are an effective way of removing search constraints. When applied in the design, evolutionary principles can be used to explain the variations in genotypes. Bentley and Corne (Bentley, 2002) suggest interactive techniques that use generalized information to achieve creative and innovative solutions.

This research follows the following framework proposed by Peter Bentley (Bentley, 2002) that contains five elements to construct a creative evolutionary system:

- An evolutionary algorithm
- A genetic representation
- An embryogeny (mapping process) using components
- A phenotype representation
- Fitness function(s) and/or processing or user input

To summarize, in order to produce new solutions, a creative evolutionary system needs some kind of evolutionary algorithm. The genotypes identified by the genetic representation are updated by the algorithm and should be designed to reduce disruption caused by the genetic operator. The genotype should be decoded by embryogeny, and the phenotype should be built using some kind of component.

The phenotype representation should be designed to allow the fitness function(s) to be evaluated quickly and efficiently (Menges, 2011). The evolutionary algorithm forms the core of an evolutionary system, and from all types of EAs in use today, this research implements a Genetic algorithm to achieve its goals.

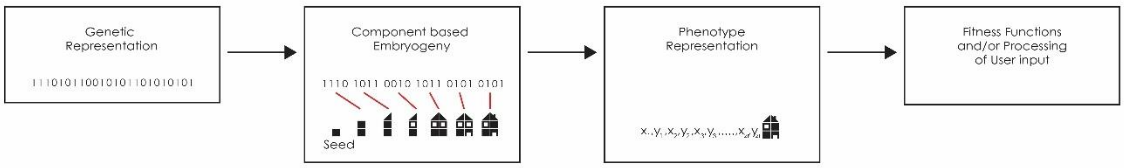


Figure 12 *Evolutionary Algorithm (Bentley, 2002)*

2.1.3.4 Evolutionary Development

In order to comprehend evolution, Charles Darwin (1859) emphasised the importance of the developing stage (embryology). However, any link between development and evolution was at that time disregarded in the theory of evolution due to Mendel's genetic studies on the origin of biological heredity. (Mendel, 1866) Additionally, this field of research was viewed as a "black box" due to the lack of understanding (Hall, 2012). An agreement was reached that alterations and mutations to genes are the causes of morphological attributes in the evolutionary process thanks to genetic advancements and the birth of modern synthesis (Wittkopp and Kalay, 2012). Sadier stated that improvements in research methodology and instruments make this field of study simpler to pursue (Sadier, 2016).

The origin of morphological variation among species was contested in the late 20th century following the identification of regulatory areas in the genome. These discoveries increased our knowledge of the role played by the genetic toolbox of organisms at different developmental stages and provided a stronger case for the emergence of phenotypic diversity (Carroll, 1995). It was discovered that genetic toolkits are maintained throughout the evolutionary histories of species and across various kinds, which in fact, reinforced the notion of common descent between species (Carroll, 2005). The regulatory genes control the expression or repression of the genes in an organism during its developmental stage. Contextual factors and ecological forces may affect this process. It was also recognised that this genetic toolbox formed morphological attributes through growing modules, each of which had its own toolkit (Schneider and Amemiya, 2016).

2.1.3.5 Natural Selection and Evolutionary Thinking

The following section discusses the connection between homeostasis (as a biological regulatory process) and evolution and reviews the relevance of both concepts. Darwin's discoveries had a significant impact on the typological thinking that was the foundation of early man's attempt to categorise and understand the variety of natural systems. It called attention to the distinctive qualities of individuals within a group (Mayr, 1994).

The foundation of modern evolutionary theory is Charles Darwin's theory of evolution (Darwin, 1859), which advocates "descent with modification by means of natural selection." After reading Darwin's book, Thomas Huxley exclaimed, "How exceedingly dumb to have not thought of it!" since his explanation of the mechanism behind the evolutionary process seemed so straightforward at the time. (Huxley, 1900, p. 105)

According to Mayr (1994), from the middle of the 19th century, the scientific community has placed a strong emphasis on two of Darwin's three major scientific contributions: first, the overwhelming proof for the existence of evolution, and second, evolution's logical and biological mechanisms. This was described by Muller as "an intellectual monument that is unrivalled in the history of human thinking." (Muller, 1949). Darwin's role in introducing a novel way of thought, bringing the population thinking to the scientific literature, appears to be underappreciated, as Mayr noted. Population thinking highlights the individuality of members of a collection and puts more weight on the population than a single person, in contrast to typological thinking, which was the dominant school of thought throughout the seventeenth to nineteenth centuries.

Typological thinking, which has its roots in Plato's theories of form and eidos (idea), symbolically explains the variety in nature as the shadow of a constant and unchanging collection of natural kinds. To put it another way, in typological thinking, the variation among individuals within a collective is an illusion, and the type (average of a collective) is the sole truth. The average is a statistical abstraction of a collective, and only variance is actual, yet for a populationist this is the exact opposite (Mayr, 1994). Every issue in evolutionary theory, including natural selection, is at two extremes: typological theory and population theory.

According to typological thought, natural selection is the binary survival of the fittest. Evolution is thus defined as a test mechanism for newly created 'types'. The environment picks the best types and eliminates the rest. There is no gradual change. This is based on scientific evidence. Typological thinking suggests that natural selection does not work or that other forces are involved in the evolution process. The understanding of natural selection in population thinking hinges on the notion of gradual changes and gradients. Each individual has a variety of morphological or behavioural characteristics that can make them better or worse than others. A higher proportion of these traits means a greater chance of survival and, therefore, reproduction. All attributes of an individual are essential, according to population thinking. In certain circumstances, some attributes may be considered more beneficial than others in new environments. This provides a point of reference in evolutionary processes to alter the trend of progressive changes in succeeding generations (Mayr 1994).

The genetic toolkit, according to Sean Carroll, "represents possibility; ecological factors will determine how much of its potential is realised." (Carroll, 2005, p. 182) The development of physical and behavioural features is thought to be the result of the genetic toolbox (or codes) found in the organisms' genomes. This correlation and the importance of individual distinction in a group for population survival, homeostasis, and adaptability can be linked. The realisation has occurred that the production of unique morphological attributes that lead to homeostasis and context-dependent adaptation of individuals and their collective is equally dependent on internal organisational structures, extrinsic forces on phenotype, as well as genotype. This understanding is crucial for the study and implementation of evolutionary thought as a developmental and generative paradigm in the design process (the process through which individuals in a collection adjust to successive generations of pressure from both internal organisations and external factors).

Organisms can adapt and respond in a wide spectrum of temporal domains. Multiple generations of evolutionary adaptations result in distinct morphological and behavioural traits. The ability to adapt to changes in a much shorter amount of time and species' survival at the individual or collective level is a result of homeostatic processes. The importance of procedures cannot be undervalued. Homeostatic regulation takes place across a wide range of spatial domains, both individually and collectively (Racimo, 2016).

According to Torday (2015), these regulatory processes serve as the means by which morphological attributes evolve over time and serve as a reference point for change. It is an active process to maintain a steady state for an organism's essential variables despite perturbation brought on by internal and external changes. The morphological and behavioural novelties of species have an impact on this operation and are also influenced by them. The result of this reciprocal influence may be the emergence of novel morphological characteristics in the phenotype during the developmental stage, which may be passed down through genotype to succeeding generations.

2.1.3.6 Importance of Design through Evolution

To understand the critical role of evolutionary systems in design, it is important to lay the foundation for such understanding. In this study, this means defining the foundational question, "why evolve designs?" Previous research provides various explanations and justifications to address this question, most notably the idea that evolving designs improve their functional capabilities and enhances the overall effectiveness of such designs. Other reasons have been identified in the literature (Brayer & Migayrou, 2013).

Reason 1: From the general perspective of solving general-purpose issues, evolution is an excellent solution.

While there is still much debate about the most effective evolutionary-based designs, there is a consensus among scientists and scholars that evolution produces better results. Previous research has identified examples of evolution-based designs that have been shown to work effectively and consistently as envisioned by the designers (Bentley, 1999). The most notable example in this regard leverages evolutionary algorithms to solve dynamic problems in engineering problems (Roston, 1997). This characteristic of evolutionary design is also time and money-saving because designers do not have to spend time redesigning machines every time an unknown problem arises.

Reason 2: Evolutionary designs can be used to solve problems in multiple unique evolutionary systems.

Currently, scientists and designers have not settled on an evolutionary design that solves every problem in multiple systems. However, algorithms such as Tabu search, simulated annealing and Hill-climbing have been used in the past to solve a wide range of problems (Rudolph, 1998). Notably, genetic algorithms are currently one of the more popular evolutionary systems used in automatic machines.

Reason 3: The human design process and the concept of evolution are significantly similar.

History shows that man is naturally drawn to evolution, as evidenced by the numerous design changes that have been part of recorded history. From bone knives to guns, computer systems, and now artificial intelligence and augmented reality, the human design process is evidently an evolving process. In other words, it is only natural to want to evolve machines as new knowledge emerges. This, in essence, points back to the idea that evolution in biological systems is underlined by the need to develop complex living organisms in response to changes in the environment. Researchers have made an attempt to use the idea of the genetic algorithm in the definition of evolution (Schwefel, 1995).

Reason 4: Natural evolution has inspired the most outstanding design phenomena in nature and is responsible for the outstanding achievements made by mankind.
Scientists have been interested in the process of natural evolution for as long as science itself has existed. In this quest, the realization that natural phenomena encompass the most outstanding design characteristics because of their authenticity, consistency, and lack of imperfections. Consider man's brain, for example; this is the most complex system that is known, even though no one has been able to fully explain its function and how it was designed. However, the dominant theory suggests that the human brain has gradually become more complex and more powerful over the years in response to changes in man's environment (Gould, 1975). Indeed, other research supports this assertion, suggesting that the human brain was originally a single cell that has been modified by gene expression over millions of years (Roth & Dicke, 2005). The fact that these evolutionary changes have helped man become a better survivor in the environment is supportive of the idea that evolutionary architectural designs can be used to solve some of the current design problems.

2.2 Computation and Design

Computational Design leverages computerized processes to improve transformations and forms in architectural design. This links back with the biological definition of Morphogenesis as "the formation and differentiation of tissues and organs" (Merriam Webster, 2019). Morphogenesis is a bottom-up process meaning that organisms evolve their form in response to external changes in the environment instead of changing to fit a predefined form. From a digital perspective, these environmental changes are comparable to external constraints on design systems. In architecture, these may include weather constraints, occupancy, and site. Architectural designs that use digital morphogenesis are based on algorithms that are designed to mimic biological morphogenesis and the processes of form-finding. These have been previously defined as "parametric modelling and performance-based generative techniques such as multi-agent systems or genetic algorithms"(Leach, 2009).

Architects use visual programming languages to help them visualise complex designs that they are unable to draw using raw hands. The visual programming language normally used is referred to as Grasshopper and is run in the Rhinoceros 3D computer-aided design (CAD) application. Grasshopper is majorly utilised to create generative algorithms like generative art. Most of the Grasshopper's components are designed in 3D geometry (Mahmoud and Elghazi, 2016). Moreover, the programs used can also have other forms of algorithms like textual, numeric, audio-visual and haptic applications. The mentioned topic is novel in architecture, and the references in relation to this subject are scarce; therefore, the followings are the review of the key sources.

2.2.1 Computation

‘‘Computerization is about automation, mechanisation, digitisation, and conversion. Generally, it involves the digitisation of entities or processes that are preconceived, predetermined, and well-defined. In contrast, computation is about the exploration of indeterminate, vague, unclear, and often ill-defined processes; because of its exploratory nature, computation aims at emulating or extending the human intellect. It is about rationalization, reasoning, logic, algorithm, deduction, induction, extrapolation, exploration, and estimation” (Terzidis, 2008).

In 1980, computers began appearing on every desk, and when new CAD software with advanced graphics and modelling techniques was developed, everything changed once again. The computer enabled architects to study fluidity, curved shapes, and simulation tools and to incorporate them into their architectural design (Aziz and El Sherif, 2016). The computer provided designers and engineers with effective optimisation tools that mimicked evolutionary processes to aid in the creation of the optimal design. Since 1960, computer scientists have investigated methods for developing genetic algorithms capable of simulating evolution and natural selection in order to overcome design challenges and introduce semi-automatic software.

The 1990s witnessed the implementation of these algorithms into architectural designs and artefact design software by architects. Computers are increasingly extensively used in the design process, where their functions range from sketching and modelling to sophisticated knowledge-based processing of architectural data. Computers are also highly beneficial in the building stage since complex shapes and geometries cannot be built in conventional approaches. (Aziz and El Sherif, 2016)

2.2.2 Computational Design Thinking

Computerised operations are sometimes falsely referred to as computer-aided because most people find it challenging to distinguish computer devices from the mode of usage. The incorporation of computer technology into the architectural design is critical in the creation of evolutionary physical spaces. Warren McCulloch defines equipment used in architecture as architecture machines (Menges & Ahlquist, 2011).

The main reason for adopting computational design thinking in this research is to establish a methodology for the architects to follow that could be generalised and used by designers and architects for the early design phase of adaptive building skins. Moreover, by combining the passive characteristics of the geranium stem with EA principles in architecture, the research aimed to propose a new design method for designing facades that could be active to the occupants' needs in terms of solar and temperature comfort. Taking into consideration the aims of the project, EA will prove very useful in assisting design and developing a facade that will simultaneously respond to human and weather conditions.

“Towards an Intelligent Architecture” (Wit, 2014) documents techniques that can be used to enhance the architectural design thinking process, which architects can use when developing the proposed intelligent facade. Smart and adaptable architectural systems are becoming more ingrained within the essence of fabrication and design. Buildings can be enabled to sense daylighting, occupation and temperature, among other variables making it easier to monitor external and internal environmental conditions as well as energy. The continual communication between personalised technologies found within the building sites and their building system integrations make it possible for architects to observe and manipulate the internal conditions. Although these systems are built on outdated architectural frameworks, fabrication methodologies, and materials platforms which cannot be changed, during the design phase, these elements can be identified as fixed variables. These finite elements limit a project’s level of innovation and customization, which means that they can slightly adjust to programmatic changes resulting in small and schematic motions (Gramazio & Kohler, 2014).

2.2.3 Parametric and Generative Design

The idea of parametric design refers to and entails modelling components that have the ability to change geometrical characteristics when their dimension value is modified (Parametric Modelling, Process, Advantages and Parametric Modelling Tools , 2019). Parametric design allows designers to "define relationships between elements or groups of elements, and to assign values or expressions to organize and control those definitions." Usually, parametric designers embed such designs with CAD programs and algorithms to take advantage of interconnectivity and the relationship between various elements of a design. These algorithms capture discrete information such as the model and manufacturer's data and operating constraints. Previous research shows that parametric designs are an effective way for designers to overcome the challenges posed by traditional CAD designs (Aish & Woodbury, 2005; Camba et al., 2016).

Generative designs mimic the evolution process to improve traditional architectural designs. McKnight (2017) states that "generative design allows for a more integrated workflow between designer/engineer and computer. In effect, they both become co-creators of the final design." Unlike parametric designs, generative design models are designed to function manually, semi-automatically and automatically. Generative designs are a comparatively new technology that is still being explored for practical application.

Some of the typical features in generative designs include:

- Increased efficacy: Unlike traditional designs, generative designs are more effective because they take advantage of iterative technologies.
- Enhanced performance: Generative designs are designed in a way that optimies structural requirements such as performance and stiffness.
- Improved development time: The advances in computing allow designers to experiment with various designs within a short period of time.
- Enhanced creativity: The use of computing technology means that engineers can be more creative and take advantage of the various options available at their disposal.
- Weight saving: Most typical generative designs are designed to be significantly lighter than traditional designs.

Looking at the potential benefits, it is evident that generative technologies are a promising technology with the potential to address some of the common practical challenges in the design of bespoke buildings. For example, there is evidence to show that generative designs are a viable solution for designing spatial layouts that maximize exposure to climatic conditions such as daylight (Skou, 2013). Additionally, generative designs have been shown to be more cost-effective in terms of the overall design process. Research also shows that the use of generative designs facilitates collaboration among various stakeholders (such as contractors and clients) in the design and devilment process, for example, by enhancing the process of scheduling.

2.2.4 Design Algorithmic Architecture

An algorithm explains a computational process for handling a problem in a limited way. It comprises deduction, abstraction, structured logic, induction, and generalisation. It is the extraction of logical principles in a systematic way and the creation of a generic solution plan. The strategies used make use of the search for universal principles, repetitive patterns, and inductive links and are interchangeable. The capability to deduce novel knowledge and to extend specific restrictions of the human intellect depends on the intellectual power of an algorithm (Menges & Ahlquist, 2011).

Generative and parametric designs usually apply graphic interfaces that preserve some understanding with traditional CAD software systems, although they greatly enlarge the capability of the computer to inform the design process. Instead of just perceiving the computer as an interface, they interact with its interior functions via programming to enable the exploitation of its abilities. Due to its investigative abilities, computation targets to imitate or enlarge the human intellect. It is concerned with rationalization, reasoning logic, exploration, induction, algorithm, extrapolation, deduction, and estimation. In the case of computerization, the ideologies are in existence in the mind of the architect and are interpreted into digital data via the software interface of the computer (Dunn, 2012). In contrast, algorithmic architecture applies a 'scripting language' that makes it possible for the designer to directly access the computational capability of the computer. Although this possibility assumes a strengthening approach to working, there are two primary factors to take into consideration. The first one is related to the 'process' of an algorithm that needs specification in a gradational way for it to create its logic efficiently. The second issue is about the needed accuracy of an algorithm because a simple mistake, like an erroneous character, will usually lead to it being unable to function or 'run' appropriately (Menges & Ahlquist, 2011).

2.2.5 Morphogenesis[5] and its Applications

Morphogenesis refers to the evolutionary advancement of form in an organism or part thereof. Comprehending that living organisms can be perceived as systems and that these change their usual multifaceted forms and behavioural sequences because of the interactions between their components over time implies that it is possible to stimulate dynamic, biological developments and transformation (Grober, 2010). Significant to the theme of morphogenesis is the idea of 'emergence' that has achieved expanding popularity in a variety of fields because it is connected, amongst other areas, to complexity theory, cybernetics, and evolutionary biology. Emergence is perhaps most easily comprehended as those features of a system that cannot be recognized from its individual components. Emergence is of instantaneous significance to architecture, calling for substantial changes to the way designs are produced. Measures for selection of the "fittest" may be created that match the architectural needs of performance, considering structural integrity and "buildability."

[5] Described by Stanislay Roudavski (2009) as a concept similar to biological morphogenesis. Morphogenesis in architecture are methods and tools used in the development of forms that can adapt to an environment. Morphogenesis gradually develops through adaptation or growth resulting in parallels which can be seen in emergent self-organization and properties.

Moreover, although the application of computational processes to operate morphogenetic design algorithms is moderately new, architects have been involved with the idea of form finding for much longer than this (Weinstock, 2004).

One significant example in which morphogenesis was applied is in the Faulders Studio + Studio M-Airspace, Tokyo, 2007. Thom Faulders was tasked to develop a screen facade that would provide the building with an identifiable identity in its instant environment. Moreover, it was created to give privacy from the street for occupants of open-plan private residences and barrier the weather from outside terraces and walkways (Dunn, 2012). The screen facade joins the isolated “Living Unit” blocks of the building’s top floors with the commercial spaces and landscaped areas beneath. The conceptual direction of the screen was influenced by the porous layers of dense vegetation surrounding the original residence (Dunn, 2012). Taking into consideration the transitory biomorphic and atmospheric features of the original 4m-deep green space, a novel synthetic buffer zone was developed. To accomplish this novel protective atmosphere, rich in intricacy and concreteness, a layered skin system isolated by an air gap was constructed to envelop the building as a non-uniform porous mesh.

2.2.6 Agent-based Modelling and Autonomous Characters

The agent-based approach emphasises the importance of learning through organism-environment interaction (Aschwanden, 2012). This approach is part of a recent trend in computational models of learning and development toward studying autonomous organisms that are embedded in virtual or real environments. In this project, a pioneering concept in facade optimisation is introduced by highlighting the role of agent-based modelling in measuring users' thermal comfort in buildings.

A particular category of autonomous agent used in computer animation and interactive media like games and virtual reality is called an autonomous character. These characters are represented by agents, who can also improvise some of their actions. This contrasts with a character in an animated movie, whose actions are pre-written, and a virtual reality or game "avatar," whose actions are controlled in real-time by a human player or participant. In video games, non-player characters are another name for autonomous characters (Reynolds, 2002).

An autonomous character in improvisational theatre must combine elements of an autonomous robot with some acting abilities of a human. The majority of the time, these characters are not human actors or actual robots, but they do share some of their characteristics. The following aims to locate the terminology of this research in relation to that of other academic disciplines since the term "autonomous agent" is used in a variety of contexts. An autonomous agent may exist in isolation or in a shared scenario with other entities. An illustration of the former is a "data mining" agent, and an illustration of the latter is a power grid controller. A situated agent may be instinctive and stimulus-driven or deliberative ("intellectual" in the conventional AI sense). Softbots, knowbots, and information agents are examples of autonomous agents that only deal with abstract information. An autonomous agent can also take the form of a physical manifestation (a typical industrial robot or an autonomous vehicle). Different classes of autonomous agents are defined by combinations of situated, reactive, and embodied. (Reynolds, 2002).

Agents

Agents are intelligent machines with the ability to (1) detect their surroundings, (2) make decisions based on an internal set of preferences, and (3) respond in a dynamic system. The agents continually reevaluate their decisions to adapt to their surroundings. (Aschwanden et al., 2009; Aschwanden et al., 2011). Each agent consists of a brain and a physical body with individual abilities. To interact, they are trained to hear and emit sound, read and paint the ground, and track other objects and have interactions. In the following, each agent type is described:

Pedestrian-agents

Pedestrian agents communicate with other agents by emitting sound at a particular frequency that is perceivable to them. They can hear, see, and read the ground (Gibson, 1979). The ability to hear enables the pedestrian agents to recognise various city functions. The agents emit various frequencies to let other agents know about their condition (Egges et al., 2004). To prevent collisions with other moving objects, the agent uses vision. The agent can change its parameters and habits depending on whether it enters a public courtyard or a private courtyard due to its ability to read the ground (LeBon, 1985; Brooks, 1991; Helbing and Molnar, 1995; Helbing, Farkas, and Vicsek, 2000; Karunakaran, 2005; Narain, Golas, and Curtis, 2009). The agent can map a coloured graph of its experience, such as stress, exhaustion, decision-making, etc., onto the terrain as it travels.

Decisions

A probabilistic socio-statistical model underlies the decision-making process in ABM (Schenk, 1995). Each agent has a unique set of preferences for each function, and it calculates its distance from each preference to determine its next objective (Zipf, 1949). A decision is made by combining the distance and preference data sets. The agent selects a new POI (Point of Interest) when they arrive at the first one because the previously visited locations are not in competition. The number of POIs visited can range from 1 to 3.

The term "behaviour" has numerous interpretations. It can refer to a complex action taken by a person or another animal out of free will or instinct. It can refer to either the complex actions of a chaotic system or the largely predictable actions of a simple mechanical system. It is occasionally used as a substitute for "animation" in virtual reality and multimedia applications. The term "behaviour" in this study is used to describe the improvised and lifelike actions of an autonomous character (Reynolds, 2002).

By breaking down a character's behaviour into different layers, it is possible to comprehend an autonomous character's behaviour better. These layers serve only to provide clarity and specificity in the discussion that will come next (section 3.2.4). Figure 13 illustrates a hierarchy of three layers for the selection of actions, steering, and locomotion for autonomous characters. There are further conceivable dissections. A similar three-layer hierarchy is described by Blumberg and Galyean (Blumberg, 1995); they call the layers: motivation, task, and motor.

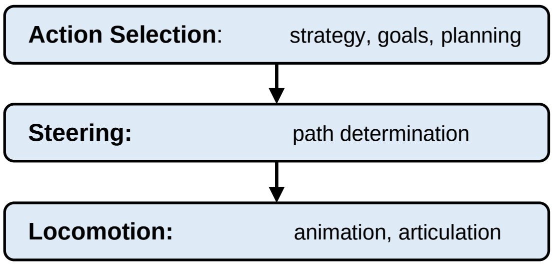


***Figure 13** Hierarchy of three layers (Reynolds, 2002)*

This project uses the pedestrian simulation plug-in in Grasshopper. People move through PedSim[6] from Start Gate to Destination Gate while choosing the best path and avoiding other people and obstacles. If they come across a target of interest, they will go there, stay there for a bit, and then reroute to the destination gate. The agents (Figure 14) will be moving on foot or stay static (Peng, 2019). The focus of the second phase of this project lies on the pedestrian agents as an evaluation tool of the thermal heat of the buildings. The areas that agents spend the most on the building determine

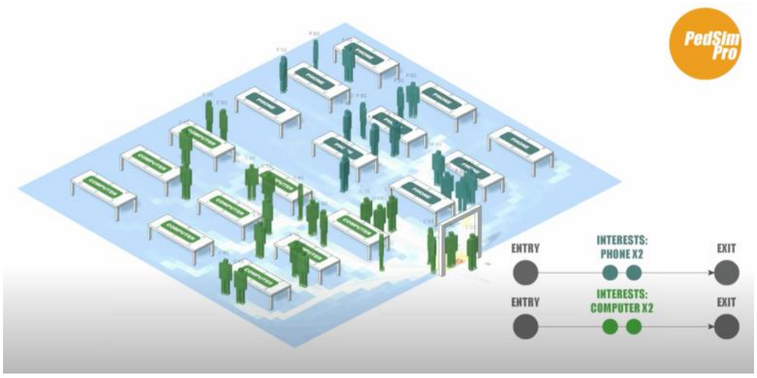


***Figure 14** PedSim pedestrian simulation plug-in in Grasshopper (Peng, 2019)*

[6] PedSim is the most popular pedestrian simulation plug-in in Grasshoper. It is the predecessor of PedSim Pro.

the type of shading the building skin should have in order to respond to the users' thermal and visual comfort. The pedestrian agents first specify their objectives based on the pre-set preferences and proximity. The way of transportation might be varied from walking to public transit depending on the simulation purposes. (Aschwanden, 2012).

2.2.7 Cybernetics and Its Relevance in Architecture

One of the formal definitions of cybernetics is presented in the current literature. Thus, it is “the science of control and data processing in animals, machines and society.” (Novikov, 2016) Some of the typical features of cybernetics are defined in the current literature sources. Most notably, cybernetics leverages scientific cognition and analysis. Cybernetics has been part of natural processes and has been around long as life. However, the concept was popularized for its relevance in modern times in Norbert Wiener's book "Cybernetics" (Wiener, 1948). Winner also introduced the idea of communication in machines akin to animals. His writings were significant because he set the stage for other scientists to explore how the mechanisms of control and communication could be applied to machines. Conway, Siegelman, & Alexanderson, (2006) are other technology enthusiasts who have explored the concept of cybernetics and have attempted to describe goal-based core interactions in mechanical systems. Today, considerable evidence shows that cyber genetics is a critical characteristic in biological systems which can be applied to improve machine technology.

Scientists have shown that it is possible and effective to design systems that mimic the biological processes of control, regulation and adjustment in response to feedback (Schmidt, 2018). This assertion is backed by the effort to support interdisciplinary academic domains such as biological engineering, biology, sociology, economics, and design (figure 1, page 7). Such academic disciplines emphasize a method of thinking that attempts to understand the relationship between concepts such as self-organisation, adaptation and output. According to Pask (1969), this form of thinking is the basis for comprehending the idea of having active architectural designs. Of course, this defies the traditional way of designing buildings as static objects that could not respond to human input. From a theoretical perspective, cybernetics enhances computational thinking in architecture by introducing the idea that architectural designs can be designed in a way that predicts their function.

Cybernetics has also been defined based on its interdisciplinary nature. According to Wiener, cybernetics has historically sought to unite various scientific disciplines with the aim of developing solutions to comparable problems (Wiener, 1948). Specifically, that it is at the “junction of mathematics, logic, communication, semiotics, physiology, biology and sociology” (Novikov, 2016). System analysis theories, general systems, informatics and metascience, are also often considered as part of cybernetics. Other authors have identified a special aspect of cybernetics which is an abstraction of Wiener’s original definition of cybernetics. This special aspect encompasses disciplines such as socio-economic and biological cybernetics. As a multidisciplinary field of research, cybernetics (in this study) investigates the application of principles of regulating mechanisms of homeostasis in the design procedures of the artefacts to carry out predictive attributes in response to environmental changes.

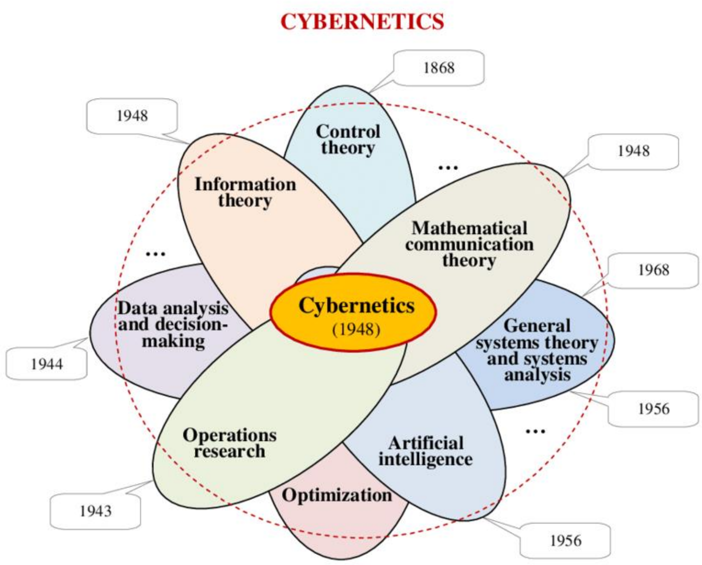


Figure 15 *The composition and structure of cybernetics (Novikov, 2016)*

2.2.8 Discussion

The crucial component in the homeostatic procedures that have also been explored by other fields is the feedback mechanisms. In response to unexpected events, these processes enable organisms to exhibit responsive behaviours. The fundamental ideas underlying these controlling processes had a profound influence on other scientific fields and paved the way for their application in other fields.

The foundational concepts of biological system homeostasis and feedback mechanisms provided the basis for the multidisciplinary field of cybernetics. The extensive study of control patterns in natural systems by D. and K. Stanley Jones (1960) shed light on the interaction between the physical structures of species and their homeostatic processes (Stanley-Jones et al., 2014). Norbert Weiner 1985 established the school of thought known as "cybernetics" by relating biological concepts of homeostasis prediction and feedback to the designed artefacts (machines) (Wiener, 1948).

This connection created a novel mode of thought about the artefact and how it relates to its setting. As of the late 20th century, there has been a growing interest in the ability of a machine or artefact to conduct predictive behaviours. As a multidisciplinary area of study, cybernetics can lead research towards finding an answer for the applicability of biological adaptation lessons in the design procedure to predict behaviours that adapt to fluctuations in varying environmental conditions.

Based on the study undertaken in this research, morphological attributes of an organism play a significant role in a biological system's capacity to detect and respond to an unfavourable change (principles of homeostasis). The evolution of these morphological attributes through a protracted process of population evolution and adaptation is essential in supporting the regulatory behaviours of each individual species.

In order to enable a variety of regulatory behaviours to change, an item that is built and positioned in a varying condition environment must have developed morphological attributes, as Simon argued: (Simon, 1996, p. 161). Applying a set of homeostasis-inspired principles to genotype and phenotype in an evolutionary model may result in the development of adaptable and morphological attributes that are responsive. As a result, the emerged characteristics can support a variety of adaptation qualities in response to unanticipated events. In the context of this research, the artefact is building skin tissue.

2.3 State of the Art

2.3.1 Buildings Skins, Shading Systems

In most cases, facades are created to be responsive to diverse situations and perform roles that can be paradoxical to each other. For example, ventilation is compared against views and energy generation, and daylighting is compared to energy efficiency. Taking into consideration that several environmental parameters may influence the standards of indoor spaces and the satisfaction of the users, several types of research have been carried out to determine the strategies of design that can develop indoor environments in alignment with the users' behaviour and locality of the buildings (Mahmoud and Elghazi, 2016).

In this study, an intelligently designed facade is described as the application of environmental control systems that are responsive to external factors and have been designed based on those parameters.

In the last two decades, progresses in electronic control systems have advanced to a level where it is possible to illustrate a building as intelligent instead of responsive.

In kinetic facades, the facades are not only neutral elevation that isolates the interior and exterior of the building (Mahmoud and Elghazi, 2016). Unlike other facades, kinetic facades develop dynamic elements that result in the buildings being more interactive with their backgrounds and their surroundings. These elements are referred to as a constant envelope of tectonic, aesthetical, and environmental association between the inside and the outside of the skin.

2.3.1.1 Requirement for Optimum Designed Façade

The design of facades is connected to daylighting and energy performances. Taking this into account, intelligent facades are presumed to be an inventive answer to the improvement of sustainability in structured environments. The word intelligent is, nonetheless, regularly applied with no detailed comprehension of the intricacy needed past the usual descriptions like responsive, adaptive, and interactive. It is widely apprehended that an intelligent envelope system needs to be active. That is, be in a position to transform its primary operational parameters in alignment with the dynamic demands of the varying environments. In addition, intelligent envelopes must be designed using smart substances that are self-actuating and self-powering. The objective of an intelligent building skin, like in the case of kinetic facades, is to optimize the systems of the building moderately to the environment, human satisfaction, and energy balance, normally depending on predictive models (Ahmed, Abel-Rahman and Ali, 2015).

One solution that is effective in such conditions is the application of 'adaptive' facade systems having their features controlled to accomplish functioning behaviour as a response to indoor and varying outdoor situations. In the deemed "best new solutions," the facades serve several corresponding responsibilities in the provision of natural ventilation, thermal, and daylight tempering. However, this needs a high level of incorporation that needs to be thought of in the initial stages of the design process (Ahmed, Abel-Rahman and Ali, 2015).

The facade, as the major component of the building envelope and a boundary between interior and exterior environments, affects the generation of electricity and attenuation of sound. Thus, both thermal and visual comforts are achieved when facades are able to achieve the following: solar load control from outside to inside, high utilisation of passive solar gains, high utilisation of daylight, protection against glare from outside, air flows between inside and outside (both ways), allow for a view to the outside, allow for privacy, rejection of heat, exploration pressure differentials ventilation chimneys (Ahmed, Abel-Rahman and Ali, 2015).

2.3.1.2 Users Requirements

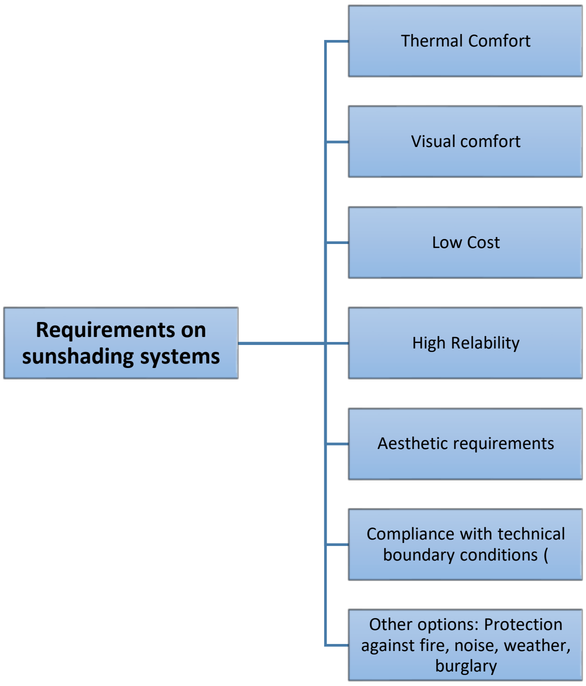


Figure 16 *User requirements for optimum designed façade (Kuhn, 2001)*

The diagram above (Figure 16) reveals the requirements for sun-shading systems. Thermal and daylight requirements are the most significant factors that determine the behaviour of the users. The requirements listed above encompass a variety of aspects: some are essential for a product's selection; others help in determining how a system is applied (Kuhn, Bühler and Platzer, 2001).

2.4 Bespoke Designs and Solutions for Particular Buildings:

The following are some related examples where exclusive designs are used to illustrate responsive façades in action. In this study, these types of exclusive designs are not considered as a precedent as it is not possible to generalize these facade designs and apply them to other buildings. This implies that they go into a different category and are not the desired type of facades for this study. Some of these exclusive designs include:

- **Flectofins by ITKE**

The valvular pollination method found in the Strelitzia reginae flower inspired this innovation. Flectofin is a louvre system with no hinges that is able to shift its fin 90 degrees through accumulating forces in the spike, resulting from the disarticulation of support or alteration of heat in the lamina

(Lopez et al., 2017). Among the broad ranges of uses of the Flectofin conception is as a responsive shading system on the outside. This design is founded on multiple motor-powered movable parts and hence is affected by friction.

Figure 17 *Flectofins by ITKE (López, 2017)*

- **The One Ocean Thematic Pavilion**

It is an adaptive envelope system that was created as an inspiration for the movements of plants and kinematic means similar to that of Flectofin. A shading system comprising vaguely bent plates may respond to different light situations and physical structure managing and reacting to varying sunlight situations throughout the day (Lopez et al., 2017). One of the main challenges of this envelope is the friction related to the moving parts of the design. Due to friction, the design makes squealing noises. The pavilion’s cover is dependent on the movements observable in spruce cones as a reflex.

Figure 18 *The One Ocean Thematic Pavilion (López, 2017)*

- **Meteorosensitive pavilion called HygroSkin**

reaction to adjustments in humidity. HygroSkin utilizes the reactive capability of the substance itself; it applies comparative moisture as a green activate to engage with the surroundings. The wood's dimensional volatility with reference to humidity is used to create a weather-responsive cover that independently unwraps and closes in reaction to changes in the weather. However, none needs the provision of functioning energy or any form of automatic or electronic regulation (Lopez et al., 2017).

Figure 19 *Meteorosensitive pavilion called HygroSkin (Menges, 2012)*

- **Al-bahar Tower Abudabi**

The facade has an interactive relationship with the climate that is inspired by the opening of the morning glory flower to the sun. Moreover, the facade takes cultural cues from the mashrabiya (Lopez et al., 2017). A key challenge in the design of the Al-bahar Tower Abudabi is to ensure the design's efficiency in absorbing natural light in an area that is densely populated with climate-controlled skyscrapers that block natural light.

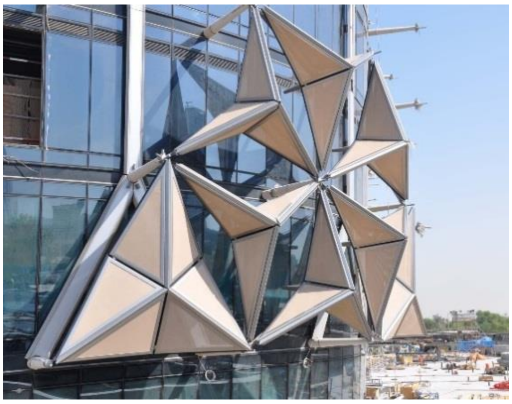


Figure 20 *Al-bahar Tower Abu Dhabi (Al Bahr Towers, 2011)*

2.5 Non-Exclusive Facade Designs (Conventional Shading Systems That Can Be Generalised and Applied to Different Buildings' Facades)

2.5.1 Types: Active and Passive Shading Systems

Active shading strategies aim to accomplish a balance between adequate daylighting degrees, giving solar guard and energy balance, while making it possible for the users to have flexibility in controlling the shading devices depending on their changing requirements. Active shading strategies describe the systems that seem to transform their features as a response to the outside climate and inside needs. The application of active shading systems reduces the unwanted solar heat increase, enhances daylight, offers regulation for the occupants, can produce immediate energy and maximize the application of natural airing. The active systems may be in the glazing of the openings or as an exterior shading system (Kuhn, Bühler and Platzer, 2001). This is normally accomplished via the application of smart glazing technologies, control and sensor systems, or via the use of smart, active shading systems.

On the other hand, traditional passive shading systems are generally classified first as internal or external, depending on the position of the device. Passive shading systems have been identified to be effective in regulating heat increase and glaring in structures and minimizing cooling energy and price minimizations in various environmental settings (Al Dakheel and Tabet Aoul, 2017). If compared, external shading systems are more effectual than internal shading systems because they are extra effective in minimizing the cooling loads of structures in areas that have hot climates. Passive shading systems have, nonetheless, their disadvantages, the mainly significant being the incapability to the external conditions changes and blocking the view to the exterior. This incapability has been a stimulus in this research to understand how it would be possible to make passive shadings adaptive to their environment. Therefore, this project focuses on optimising the passive response of shading systems by using Evolutionary Algorithms as well as finding the limitations of conventional passive shadings, which leads to having a better understanding of gaps in the knowledge and results in proposing practical solutions.

2.5.2 Active Shading Systems

Active shading systems are grouped into three major groups: these include

(i) the glazing in the type of smart glazing (Smart Glazing Systems)

These systems contain glasses whose light transmission features are modified either to be transparent or translucent depending on the light, voltage or heat applied. They apply smart windows that regulate the transmission of light into and out of the building. Examples include electrochromic devices, suspended particle devices, and liquid crystal devices (Baetens et al., 2010).

(ii) kinetic external shading systems

These systems make it possible for a building to minimize the cooling and lighting loads. They operate by being responsive to the chemical, mechanical or electrical stimuli through which sliding, folding, shrinking, expanding, and transformation in the shading devices occur. Examples include rotating shading systems and folding shading systems (Moloney, 2011).

(iii) Shading devices that integrate energy production (integration of renewable energy systems)

These systems utilize renewable sources of energy like solar. Examples include algae facade systems, PV shading devices, and solar collectors integrated shading devices (ElSayed, 2016).

2.5.2.1 Different Types of Active Shading Systems and Their Limitations

One of the main challenges of using active shading systems is that they are expensive, especially since the technology is still relatively new. In smart glass, the transformation between opaque and transparent might also take several minutes. Some smart glass technology may also require electricity to transform, which may be problematic in case of power shortages. The following section discusses the limitations of the different types of active shading systems.

I. Electrochromic Glazing

- Extreme amplified surface temperature and sluggish bloom procedure

A typical challenge is extreme surface temperatures which are usually due to the fabrication of stable electrodes (Eh et al., 2018). The issue of the blooming effect and its effect on conductivity has also been discussed in the literature. According to Jensen et al., the blooming effect is caused by variation in surface resistance, which leads to accelerated switching responses. A possible solution for this issue involves homogenising the electric field distribution in the Electrochromic device leading to homogeneous colouration.

- Low durability for electrochromic glazing

One of the major drawbacks of electrochromic glazing systems is related to their durability. Generally, the glass used in electrochromic glazing lasts an average of ten years which is a significantly short duration compared to traditional glazing systems. Eh et al. (2018) This challenge is compounded significantly by the high cost required to install a working electrochromic glazing system.

- The optical features that modify the switching electrochromic are unknown

Commercial electrochromic windows seem to be an effective technique for reducing lighting energy and heating loads in buildings particularly due to their computability with substrates coupled with low power consumption. However, more research is needed to develop effective optical switching to modulate the transmittance of the solar spectrum. As Eh et al. (2018) note, accurate switching requires well-controlled operating environments, especially window properties. This is often challenging because window properties may vary constantly depending on factors such as the time of active shading.

II. SPDs (Suspended particle devices)

- Reduced clearness in the SPDs' faded condition, in contrast to the EC glazing

- A haze that is not desirable

SPD windows require a tiny but constant electrical current to remain in a clear state. Like LCD windows, SPDs operate between 65-220V AC and require constant power to maintain transparency. In contrast, EC devices require power only during switching, giving them an edge over SPDs and LCDs.

III. LCD (Liquid crystal devices)

- Unsuitable in dark environments

LCD glazing is hazy, implying that it will scatter instead of absorbing light such that there will be a fog aspect when the device is in visible condition (Al Dakheel and Tabet Aoul, 2017). In most cases, the LC glazing is usually opaque or transparent and has no state in between. This can be problematic in terms of colour saturation, contrast and black level. Basically, LCDs can also fail to produce very dark and black greys, making them unsuitable for use in dark environments and dimly lit areas. A possible solution involves careful control and adjustment of contrast. Research also confirms that LCD panels are limited in that they allow for uncontrolled heat flow through the glazing. As Marchwiński (2013) 0asserts, "they do not actually exhibit variable transmission characteristics, since they only affect the way light is transferred and not the quantity of radiation that is allowed to pass through."

- LCDs use organic components

LCDs comprise organic components that are vulnerable to UV and infrared radiation. At the bandwidth of these radiations, there is a notable impact on the organic constituents in LCs. Prolonged exposure to these radiations causes a shift in colour and blurry appearance of images viewed through LCDs. With time, infrared and UV radiations damage the organic components making them inoperable.

- Overheating

LCDs are also susceptible to overheating following excess IR radiation. Liquid crystal devices are supposed to operate within a range of temperatures prescribed by the manufacturer. Outdoor use can result in higher temperatures than normal. Exposure to excess heat can make the crystal isotropic and, subsequently, fail to function as expected.

IV. Folding Shading Systems

- External Variable Conditions

External variable conditions, such as climate changes, significantly impact the performance of shading devices. In folding shading systems, the effect is on the reflectance and solar radiation and, ultimately, the overall efficiency of the systems. This is particularly true due to the fact that folding glazing systems are challenging to clean. When this sort of glazing is used in high-perched areas, the issue is more problematic.

Folded shading devices are designed to be in constant motion; therefore, deformation causes strain and stress, which usually limits their movement and may result in total material failure. 1D deformation is particularly common in Folding shading systems (Addington 2005).

- The efficiency and the movement of the folding shading systems could be limited by the variable external conditions

- Their movements are limited by the behaviour of the SMPs that are limited to 1D deformation (Addington, 2005).

V. PV (Photovoltaic) mounted shading

- In cases of higher temperatures, the power production of the PV panels is minimised

It is a well-documented fact that the performance of solar cells is highly dependent on the operating environment, specifically the temperature. Generally, for PV applications, higher temperatures lead to higher carrier concentration which in turn boosts power output and overall performance.

Conversely, low temperatures reduce power output and impact efficiency negatively because of this linear relationship between the carrier concentration levels and temperature.

- Limited tolerance to overheating due to partial shading

There are incidences of dust accumulation and limited tolerance to overheating that lowers efficiency (Yoo and Lee, 2002). This phenomenon is commonly referred to as partial shading (also be caused by shadows or cell damage) and to hot spots due to uneven illumination over the PV cells. Hot spots are typically characterized by higher-than-normal temperatures, with the compounding effect being lower reduced power output, material degradation and the overall reduction in efficiency of the devices (Garcia et al., 2003).

- There are incidences of dust accumulation and limited tolerance to overheating that lowers efficiency (Yoo and Lee, 2002).

VI. Algae Facade System

- There are cases of high maintenance costs as well as initial costs that are involved

Algae panels are costly compared to other smart devices. However, the high costs can be attributed to the fact that the technology in use is new. Additional costs are also incurred in researching, developing and designing the technology. However, the costs should fall once economies of scale, incentivization, innovation and evolution of technology come into play.

- Contamination concerns

Environmentalists have raised concerns regarding the potential dangers of some algae, like cyanobacteria. These algae constitute neurotoxins and hepatotoxins that are relatively toxic to humans. Moreover, leakages or damages can bring about unpleasant odours. These concerns make people hesitant to adopt algae façade systems.

VII. Solar Collectors Integrated Shading Devices

- These shading devices can block solar radiation and affect the amount of light entering a building leading to a limited view range to the outside for the occupants (Priatman et al., 2015).

- Complex and Expensive Execution

One major drawback to these devices is that the building of solar collectors integrated shading devices requires complex and expensive execution. Their execution requires highly skilled personnel and sophisticated equipment, which makes these devices expensive. The layers of applied paint in these collectors are extremely thin, and therefore, these collectors have to be assembled and installed with a lot of caution. Also, collectors with TSSS coatings must be applied on metal absorbers and have to be extremely thin. Moreover, in most cases, it is imperative that the paint coatings be shielded from atmospheric conditions by glazing.

- Limited range of applicable surface colour finishes

In most cases, the absorber surface is covered with TSSS coatings that either come in dark hues or are totally black. In case of widespread adoption, collectors make buildings appear unvaried.

VIII. Rotating Shading Systems

- The large size and the view range

A primary setback of rotating shading systems regards the large size of the rotating fabric panels since it incorporates both the retracting spring and the drive mechanism. Moreover, in terms of design, it is essential to ensure coordination between the support structures and allow full rotation and easy accessibility for maintenance services. Additionally, using rotating shading devices always comes with the challenge of preventing the view to the outside from being blocked.

To sum up, recent research in the field of smart materials has provided valuable insights into their potential application in building facade design, particularly within the context of biomimicry and computational design; apart from the studies mentioned above, projects by Sadegh et al. (2022), Yi and Kim (2021), Kim et al. (2023), Kuru et al. (2021), and ElDin and Abdou (2020) have explored various aspects of smart materials, showcasing their ability to mimic natural, plant-based cooling approaches in multifunctional building envelopes. Investigations into shape-memory-alloy (SMA) response and artificial intelligence (AI) kinetic control have demonstrated the feasibility of self-shaping building skins, and comparative analyses have highlighted their environmental performance. Moreover, integrating hybrid soft robot actuators and fabric membranes has been investigated to create responsive building facades with adaptive biomimetic features. Additionally, novel simulation frameworks have been developed to predict the performance of biomimetic adaptive building skins, integrating multifunctionality for enhanced energy efficiency. These findings on smart materials present valuable contributions to the existing literature and inspire the aim and direction of the proposed methodology of this PhD thesis.

2.5.3 Passive Shading Systems

Passive architecture shading incorporates different mechanisms, including the blending of conventional architectural principles with the relevant materials for building to ensure there are stable temperatures, thus ensuring there is a comfortable environment year-round. Effectively installed shading and sun control passive wall systems significantly reduce the cooling requirements as well as the peak heat gain of a building and, in turn, boost the interior quality of natural lighting. These passive solar shadings are ideal for boosting visual comfort through the regulation of glare and reduction of contrast ratios. This literature review explores different types of passive solar shadings and devices employed in building constructions. These passive solar devices are crucial for buildings since they create a chance for the differentiation of various building facades hence creating a specific human scale to undistinguished architectural designs helpful in achieving energy efficiency by allowing thermal transmission and radiation into and out of the building during warm and cold weather conditions respectively.

Different types of passive shading devices are used in many architectural designs in buildings to help in temperature regulations of the internal spaces within a building structure. They are essential in that they make it easy and efficient to control the internal house heating conditions either during warm or cold weather situations. During cold weather, without these passive solar shadings, one may have to use a lot of energy to raise temperatures to favourable levels. However, during warm weather, temperatures go high such that to lower them, it will consume a lot of energy to run fans and other air conditioning devices that are not energy efficient. This problem of maintaining efficient thermal conditioning within houses can be controlled by passive solar designs that are employed in constructing passive solar shadings. In most cases, external devices are considered better than internal ones. However, they are less common due to specific reasons like maintenance, initial cost, and aesthetic reasons. An accurate or effective shading device majorly relies on the building façade's solar orientation (Prowler 2016). Given the dramatic increase in various shading devices, the main issues in making the right choice include durability and efficiency concerns. For instance, while there are a variety of adjustable shading devices, they are limited by the aspect of practicality issues like the requirement for manual adjustments. In the modern world, there are emerging effective techniques of shading which are more reliable.

2.5.3.1 Overhangs

Overhangs are of many forms. They can be in the form of walls or aluminium window shades. They are fixed on the exterior parts of the windows in a horizontal position. Overhangs remain modern means of shading and can be effectively utilized to regulate the extreme sun rays. They also protect the house openings and walls from the rain impact. There is very little or no effect on the outside view and the movement of air in the building. In this case, the obstructions of different materials are only used for blocking the sky, whereby the light beams pass through or even the brighter parts, which have a high probability of creating temperature problems. The overhangs are also ideal for regulating wind, and the climate of a given area dictates their specific length. The exterior louvred design of the overhang placed above the solar glazing paves the way for the penetration of more daylight directly into space and, in turn, blocks any form of unwanted sun rays (Palette n.d.). Overhangs are usually ideal for shading the southern exposures, especially in the case of low-rise buildings. This ideology is highly effective, aesthetically appealing, and also an economical option for residential applications. However, overhang shadings generally have the shortcoming of low thermal capacity and high heat loss influx (Sameti and Jokar 2017). This is because of their partial shading on the solar-absorbing surfaces. Therefore, it becomes a problem to save energy during heating and cooling times since these overhangs are finite and do not offer optimal shading.

Some basic characteristics of overhangs are

- Shading:

- Very effective at shading south-facing windows in the summer
- A hot climate decreases energy consumption by 33% for cooling and 30% for heating (Al Dakheel and Aoul 2017)

- Visibility:

- Reduce the occupants' view to the outside(De Luca, Voll, and Thalfeldt 2018)

- Cost and Maintenance:

- The controlling expenses of mechanical pieces of equipment are considerably lowered (De Luca, Voll, and Thalfeldt 2018).

- Energy Saving:

- Reduce energy consumption
- Reducing direct solar gains and peak electricity demand
- Reduces design cooling capacities in the east and west-orientated facades with reductions of between approximately 40% and 50% (De Luca, Voll, and Thalfeldt 2018)

2.5.3.2 Horizontal and Vertical Louvres

Horizontal louvres are fixed on the exterior of glazed windows. They are designed with prolonged lengths, which help them in preventing summer sun and allow little of the winter sunlight radiations.

Figure 21 *Overhangs (Nature of home, 2022)*

Their disadvantage is that they prevent only a small portion of the radiation during heating times. Especially during summer, horizontal devices have the challenge of preventing afternoon solar radiation penetration into the building. Louvres are vulnerable to mechanical damage where the tilting mechanism can easily break down, making them less useful. The clips that hold the louvre slat may loosen, and louvres fall and get damaged, which may require additional costs to repair them. Louvres should be strategically designed to block sun rays during summer and allow entrance in summer times (Taleb 2014). Horizontally fixed louvres should be strategically angled to the winter sun and ensure there is accurate spacing to allow in the winter sun.

Vertical louvres are useful where the sun is directly hitting the façade from the direction of southeast or west. They are hence employed on the buildings as east or west facades. They can be designed to be responsive to the position of the sun. Vertical fins cause a vertical shadow, which can cause total shading depending on their angle positioning (Kirimtat 2016). They can hence be adjusted to allow or prevent sunlight from penetrating the building.

Other characteristics include;

- Shading:

- Indoor comfortable thermal conditions (Palmero-Marrero and Oliveira 2010)

- In hot climates, horizontal louvres decreased energy consumption by 33% for cooling and 30% for heating(Al Dakheel and Aoul 2017)

  - Visibility:
- The relation between window height and louvre width allows that closed louvres
- A higher visibility is wanted, then a lower louvre inclination angle will be necessary(Palmero-Marrero and Oliveira 2010)

  -Cost and Maintenance:
- The operating costs of mechanical equipment are significantly reduced(De Luca, Voll, and Thalfeldt 2018)

  - Energy Saving:
- Significant energy savings
- Reducing loads during the cooling season(Palmero-Marrero and Oliveira 2010)

Figure 22 *Horizontal and vertical louvers (Choi, 2022)*

2.5.3.3 Egg-crates

They are unique solar shadings with both vertical and horizontal features that prevent solar radiation and sunlight from all directions. The horizontal elements control the glare, while the vertical ones cause the shading (Utpariya and Mishra 2018). The negative aspect of egg crates is that in critical shading angles, they fail to provide seasonal shading variations. They prevent winter sunlight penetration during the period that receiving sunlight is required. Their performance is affected by internal reflection and sky-diffusing radiation, which is not directly penetrating through the egg crates. Due to their enclosure design, solar radiations get entrapped and circulate within the crates and eventually get absorbed into the building surfaces. While they are useful in avoiding optimal shading, especially in hot regions, they prevent much of the useful sunlight's radiations and interfere with the view.

Other characteristics include:

- Shading:
  - Reducing incident solar radiation on the window with maximum values of 39% in summer and 33% in mid-season(Calama-González, León-Rodríguez, and Suárez 2018)

- Visibility:
  - Improving natural illuminance levels (Calama-González, León-Rodríguez, and Suárez 2018)

- Cost and Maintenance:
  - The operating costs of mechanical equipment are significantly reduced(De Luca, Voll, and Thalfeldt 2018)

- Energy Saving:
  - Allows a better yearly performance
  - Decreasing artificial lighting consumption
  - Energy savings of air-conditioning systems (Calama-González, León-Rodríguez, and Suárez 2018)

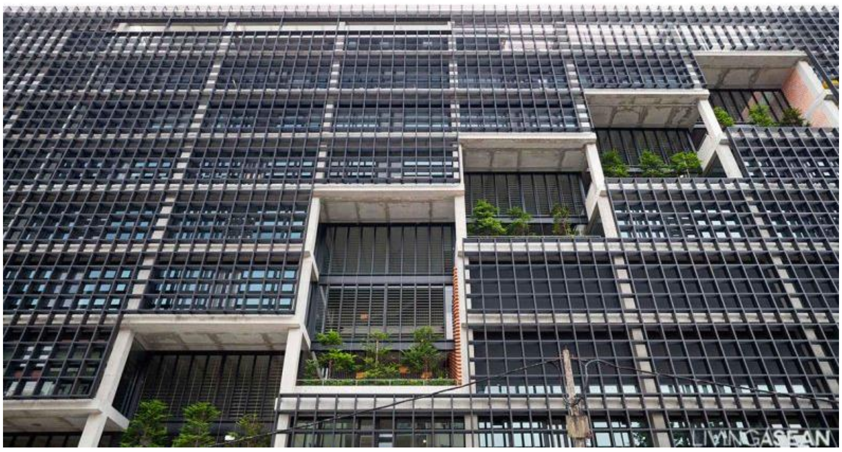


Figure 23 *Egg-crates (ResearchGate, 2017)*

2.5.3.4 The Limitations of the Passive Shading Systems

The drawbacks of using horizontal passive shading devices include the following:

1. They work less efficiently in the early morning and late afternoon, regardless of direction, when the profile angle is quite low. Devices that provide horizontal shading must be extremely lengthy and difficult to use in order to be effective at this time.

2. The passive horizontal shading devices are negatively impacted by changes in profile angle at any point. As a result, they are unable to block direct sunlight from entering the building via the window when the profile angle is low in the morning and the afternoon.

The drawbacks of using vertical passive shading devices:

1. Vertical passive shading devices impair the view of building occupants; consequently, their use is discouraged if a superior alternative is available.
2. The continual reorientation of the sun's angle poses a problem for fixed vertical shading systems. Therefore, when the solar surface angle is close to 0 degrees (nearly perpendicular to the observing facade), they are unable to shield the window from direct solar radiation. In this instance, vertical shading devices must be continuously adjusted in order to maintain their effectiveness.
3. "In general, when direct sunlight falls to the vertical shading devices, they always downward the sunlight, which impacts the distribution and illumination in the interior when the reflection is preferred as far as possible to get uniform illumination" (Aladar Olygay: Solar Control and Shading Devices). Typically. They are known to contribute less to the control of daylighting. (Olgyay, 1976)
4. When vertical shadings are employed alone, they cannot be utilised to shield windows from rain, especially during the rainy season when there is a great deal of precipitation. Consequently, receiving fresh air and circulation will be problematic.
5. When the solar surface azimuth is 0 degrees in the afternoon, North and South-facing objects cannot block sun energy. Moreover, on December 22, when declination is -23.5, they are less effective in the West, South West, and South East.

The downsides of employing crossed (egg-crate) passive shading devices are:

1. Though passive crossed shading devices are suitable to be used in different parts of the world, they are less effective at North West and North East orientation on June 22nd, when the declination is +23.5 degrees, and at South West and South East orientation on December

22nd, when the declination is - 23.5 degrees. Because at this period, the profile angle is quite low, and the sun azimuth at the surface is close to 0 degrees.

2. The combined shading devices must be regularly adjusted to follow the constantly shifting direction of the sun's angle in order to be effective in all orientations and at all times. Consequently, they will be unable to block solar radiation when the angle of the profile is very minimal and nearly perpendicular to the observing facade. (Oenardi, 1990)

2.5.4 Conclusions and Suggestions Based on Shadings' Limitations in Literature

The increasing demand for interior comfort and energy consumption in buildings has resulted in greater demand for more efficient façade systems. Facades are one of the potential solutions to the issue of energy consumption and thermal comfort. However, the commonly used active façade shading systems are typically designed to be responsive to one or several environmental conditions (Lopez et al., 2015). As this literature review has indicated, there are various inherent challenges that limit the practical application of existing shading systems. Al Dakheel and Tabet Aoul (2017). One of the biggest issues that designers have to deal with in conventional building shadings is that the majority of the existing shadings suffer from the conflicting issue of maximising the view of the occupants and minimising solar radiation exposure (Zvironaite et al., 2014). In light of the mentioned limitations of passive shadings and skins, this research has identified the following characteristics as important for a new adaptive building shading design (gap in the literature):

1. The facade's morphology should carry the (attribution) genes that make them adaptable to the environment in which they are planned to be built.
2. The adaptability of the shadings should be clearly responding to specific objectives such as view and radiation (users' thermal and visual comfort).
3. The facade should block the sun when needed but have minimum effect in blocking the view.
4. The design phase of the shadings should evolve from what is a repetitive and typical design across the building to a new generation with design morphology that speaks to the building's form and location specificity, therefore eradicating underutilised solar angles that may not be considered within a generic shading strategy having an effect on the intensive solar radiation on occupants' thermal comforts.
5. The criteria which simultaneously need to be met during the design phase of the building skin or facade fall into the following considerations: during the design phase, taking into account how the shadings need to respond with respect to the solar radiation and angle analysis over

a different period of the day, as well as the occupants' most visited area in the building (movement heatmap) to successfully achieve an efficient design.

6. It is very important that the shadings are smartly designed and customised to only target the areas where blocked solar radiation is needed (based on the users' needs in order to maximise efficiency and performance) rather than using a repetitive pattern all over the facade that sacrifices the view and only blocks radiation at certain angles.
7. Any proposed morphology for the skin should be applicable to both the freeform and geometric shape of the building.
8. A contextually-considered design exploration or analysis is required for any passive part and static morphology of the skin.
9. Building skins and facades should respond to conflicting objectives of view and thermal comfort during the design phase (Zvironaite et al., 2014).

By focusing on the points above, this study has identified the gap in the literature related to mainstream building shadings. Various researchers have proposed bio-inspired facade designs as a method of improving performance (discussed in section 2.1). The performance of such systems can be improved through the use of several integrated programmable software (Evolutionary Computation) in order to be individually customised for the different environmental and morphological conditions.

3 Research Methodology[7]

As previously mentioned, this study falls into the category of design science, which defines a distinctive class of inquiry via the use of a vast collection of behaviour, form, and holistic understanding from the natural sciences. Instead of scientific design, which combines intuitive and non-intuitive design exercises to reflect the reality of contemporary design practises, design science entails a systematic investigation of the design process through comprehension of the scientific and technological key elements of an artefact's design (Cross, 2001). This research suggests a design model that generates design solutions that are related to those features. The design model proposed in this study produces design solutions that Herbert Simon's definition of an artefact, "the artefact as interface" (Simon, 1996, p. 6), described as an interface between the inner and the outside.

The methodology used to test the hypothesis and research questions of this study initially comprised two connected stages, the evolutionary design and the Agent-Based Modelling ABM, in which the latter optimises the generated solutions of the former simulations in order to respond directly to users' comfort. The first stage reflects the insight gained through biological and building skin studies in chapter two. Through the evolutionary design phase, ways of implementing principles of adaptation lessons in biomimicry in the early-design exploration phase are established and analysed. Through the ABM phase, a collection of systematic analyses, evaluations, and objectives are suggested to respond directly to users' comfort in the building.

According to Simon (1996), it is unrealistic to predict every occurrence in the future. "What makes such design even conceivable is that we need to know or guess about the future only enough to guide the commitments we must make today. Design is unrelated to future eventualities that don't affect current commitments (Simon, 1996, p. 160). Following Simon's claim, both stages—evolutionary design and ABM, include a degree of abstraction and are carried out through a series of forecasting simulations.

[7] To provide a clear and concise overview of the rigorous methodology employed in this study, a visual representation of the research journey and methodology is presented in the following PDF: [https://drive.google.com/file/d/15_W3-uPHXVpbaI1eWx5BMAnWej5-xh1k/view?usp=sharing]. This diagram provides a clear and concise overview of the key stages and methods utilised throughout the research process.

3.1 Towards Evolved Solar Radiation Control in Building Skins

After developing the mind map (section 2.1.2.5) and addressing the potential adaptation lessons in nature, the research surveyed industry inputs in order to propose computational simulations and modelling as well as addressing gaps resulting in substantial changes to maximise productivity through reviews and feedback. The main aim of simulation and modelling is to give a description of various interdependent factors within a complex, intelligent system and provide a predictable pattern of their integration and better manage the desired results. These approaches are categorised as an experiment setup, case studies, optimisation of view, radiation and comfort.

The research methodology is based on an investigation of the techniques and behaviours that living organisms gain through evolution (natural selection) as a response to reducing the amount of solar radiation they receive. To identify potential living organisms with suitable applicability in architectural skins, the BioSkin database was extensively explored. The subsequent step involved the implementation of biomimetic adaptation lessons and inspirations from living organisms into a new skin design proposal. For this purpose, the design process was carried out using Rhino 3D, a powerful 3D modelling software, along with its plugin Grasshopper, known for its exceptional capabilities in parametric modelling. The decision to utilize Rhino 3D and Grasshopper was driven by their ability to efficiently handle the parametric nature of both proposed and existing design models in the case studies. Moreover, Grasshopper's flexibility enabled the seamless integration of biomimetic principles into the design process, fostering the exploration and testing of various design iterations.

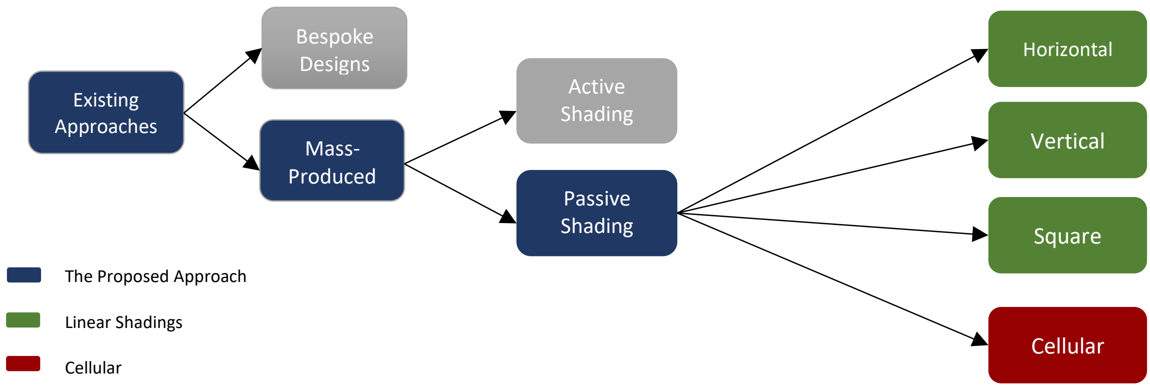


Figure 24 *The focus and the scope of the research in the world of building skin and facade*

3.1.1 Alternative Path: Rudimentary Experimentations with Active Shading Systems for Building Skins

As discussed, the main focus of this research study is on the design stage of the building skins, where the Evolutionary Algorithm can influence the performance by bringing the gap between thermal and visual comfort in building skins. However, this study initially took a path that involved experimentation with proposed active shading systems as a solution to the research problem and to achieve the study objectives.

It is important to mention that the study initially assessed both types of mass-produced shadings (active and passive). The attempts toward creating prototypes for active shading systems are explained in detail with figures and links to the related information below.

Attempt 1: Automatic and manual control of temperature and light

In this attempt, PDLC[8] films as components represent active parts of the façade that can interact with solar radiation and temperature. Below each PDLC film, there is a temperature and light sensor that can send signals to the Arduino kit[9] in order to control how much solar radiations need to be blocked in order to maintain a comfortable temperature. The goal was to keep the space behind PDLC films below 25 degrees by blocking solar rays in an automatic way, as well as provide the ability to manually control the device via mobile phone.

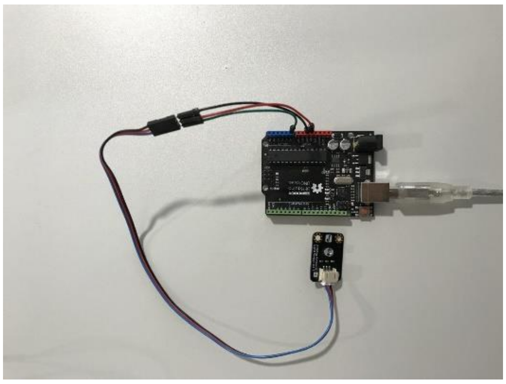


Figure 28 *Light Sensor and Arduino Kit*

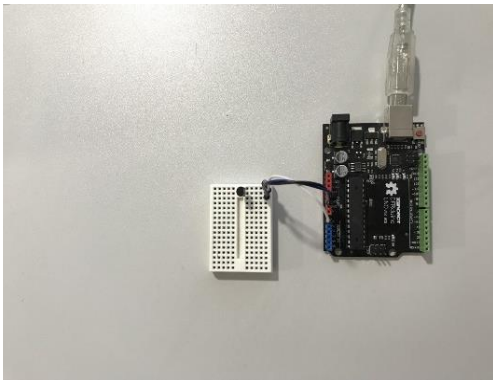


Figure 28 *Temperature sensor Arduino Kit*

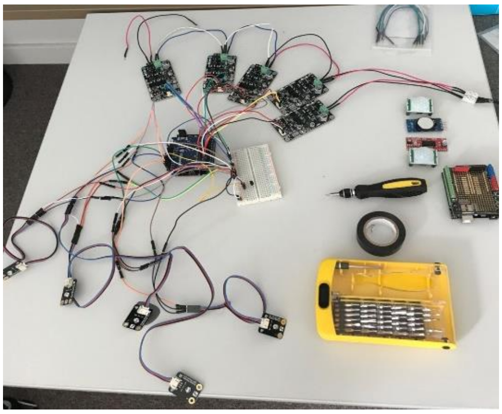


Figure 28 *An attempt towards controlling five light and one temperature sensor*

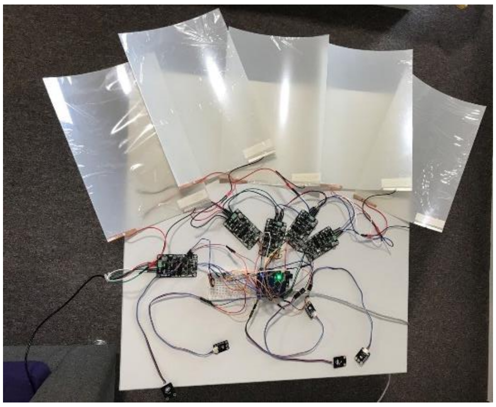


Figure 28 *PDLC films attached over light sensors*

[8] The term "PDLC film" stands for "Polymer Dispersed Liquid Crystals," which is essentially a three-dimensional structure made up of liquid crystal microdrops dispersed in a polymer matrix.
[9] The Arduino Kit consists of all the components used for building digital or electronic devices.

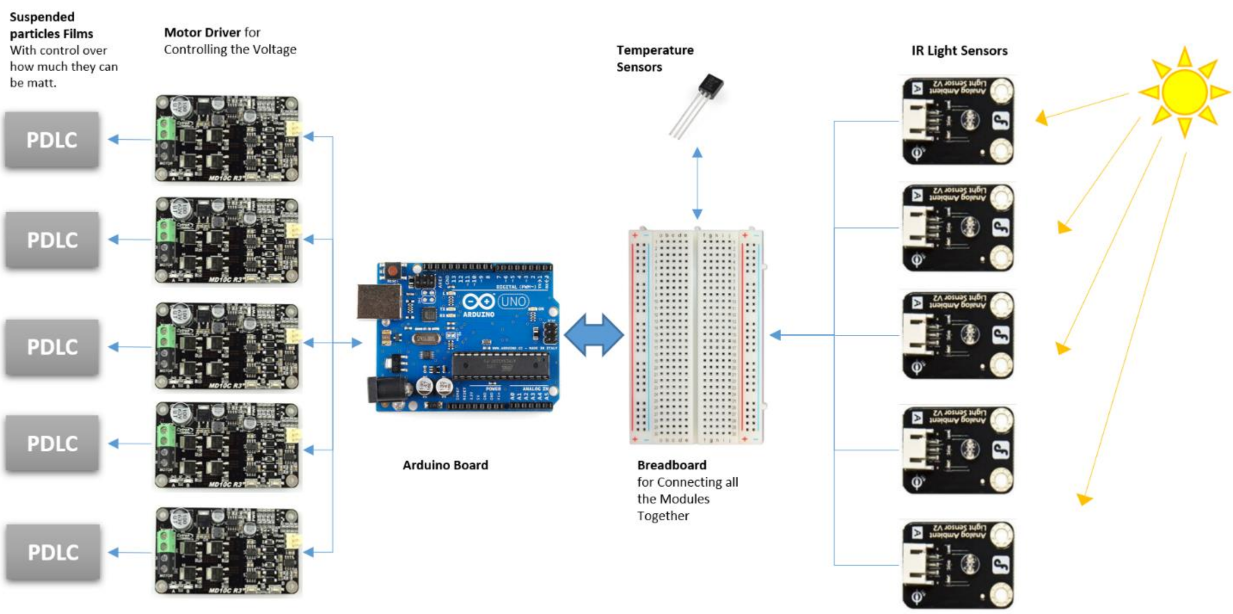


Figure 29 *The diagrammatic visualisation of input and output*

The next attempt was to place the sensors in isolated boxes and test how much-infrared light (that is, the main thermal ray emitted from the sun) is blocked via PDLC films and their smart behaviour.

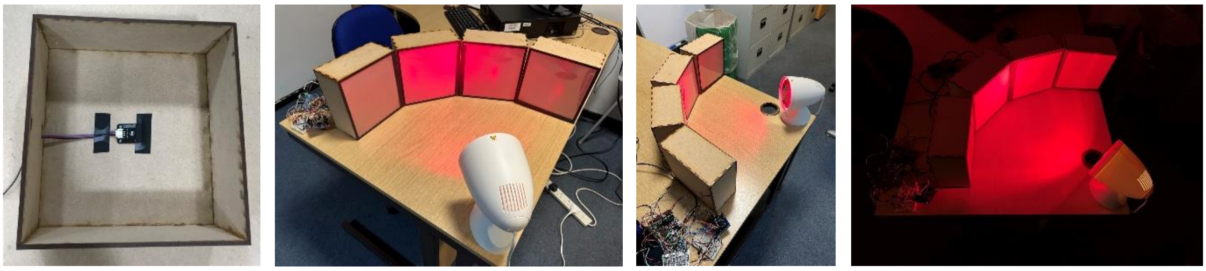


Figure 30 *Testing the PDLC performance against Infrared light with light and temperature sensor*

The next attempt was to control the system via mobile phone, and the pictures below demonstrate two ways to control it via the 1Sheeld app that links to Arduino.

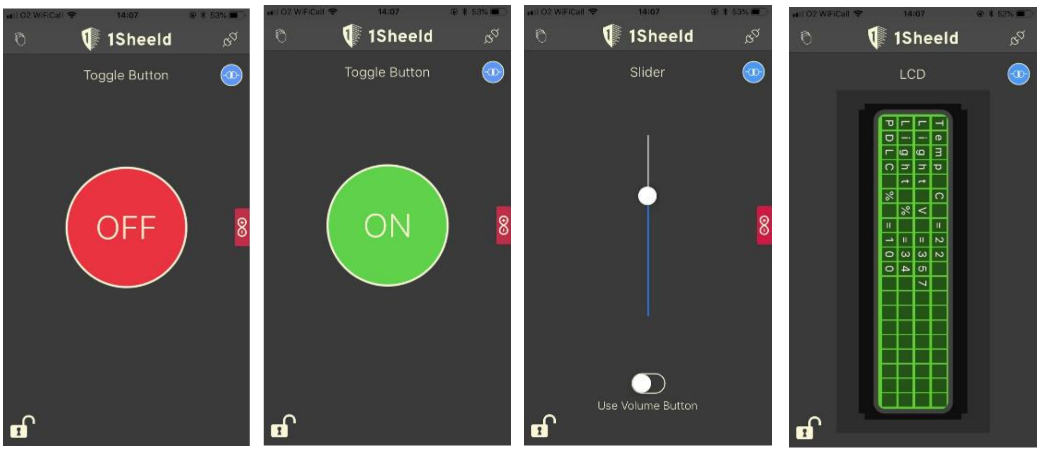


Figure 31 *Mobile app interactivity with Arduino*

The link below represents how the PDLC films are controlled via mobile phones.

https://vimeo.com/manage/videos/733151605

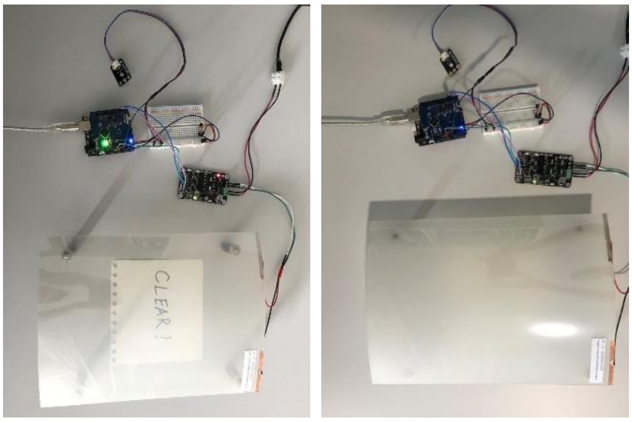


Figure 32 *Effectiveness of PDLC films in blocking light and infrared*

Attempt 2: Human interactivity with facade systems

This was an attempt to make a facade system respond to human needs by being controlled with the movement of the left and right hands. In this experiment, the right hand opens the hexagons that represent the building skin cells, and the left hand closes them. The test is illustrated in the link below. https://vimeo.com/manage/videos/733150014/privacy

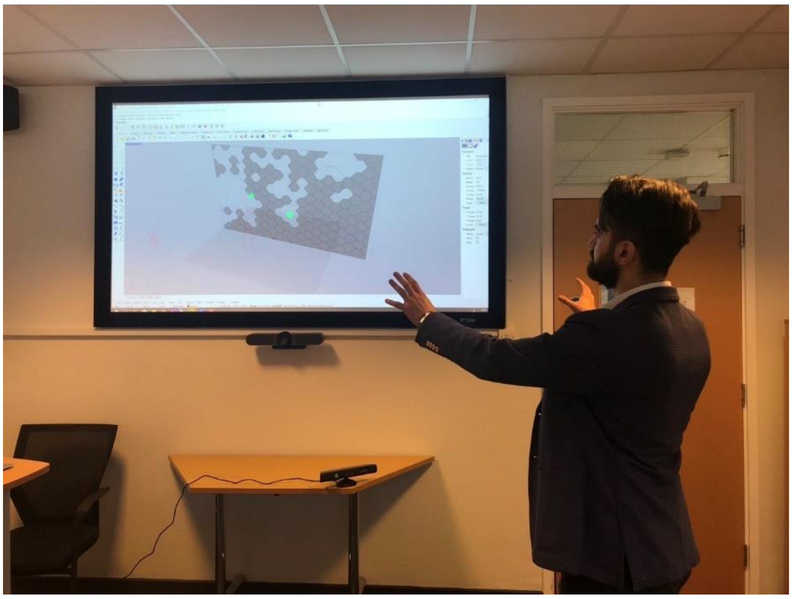


Figure 33 *Human interactivity with facade systems*

In the end, based on the literature review and the research conducted in chapter three regarding active shadings, it was evident that they cannot yet be a reliable choice due to the extremely high maintenance cost and prototyping expenses. Therefore, the study's focus was shifted towards passive shadings as a better choice to achieve the goals and objectives of this research.

3.1.2 Passive (Main) Route

As mentioned, the first stage of the methodology acquires completing an extensive and comprehensive literature review to gauge the current knowledge about how biomimicry, morphogenesis, and digital architecture can become a contribution to the development and efficiency of kinetic facade elements.

- Analysis of the relevant documents, including books, journals, articles, magazines, and archival data.
- Case studies and existing similar works in the field will be reviewed to gain a deeper understanding of a selected range of building intelligent double facades in respect of light (solar radiation) and temperature.
- Receiving support from industry professionals who have experience in digital simulations and modelling in order to learn more about parametric and algorithmic designs to deduce failure and success rates of the project and make substantial changes to maximise its productivity.

This stage involves finding inspiring adaptation lessons from living organisms as well as seeking their applicability in terms of responding to solar radiation. In order to document the findings, the data-collecting mind map (section 2.1.2.5) proposed in this research has been implemented to find out the applicability of adaptation, evolution techniques and strategies of a living organism in architectural skins. The main obtained elements from the mind map are the following:

a) Surface-to-Volume Ratio
b) Self-shading Techniques
c) Homeostasis Principals
d) Emergence, Evolution, Growth: Grouping and Partitioning Technique of Stem Cells of Plants

3.1.3 Simulations (Passive Response)

The study created an initial mind map to grasp and explore the adaptation lessons available in biology that are associated with the research aims and objectives (section 2.1.2.5). After developing the mind map (section 2.1.2.5) and addressing the potential adaptation lessons in nature, the research surveyed industry inputs to carry out the research on case studies and experimental examinations of buildings with skins designed to control solar radiation. Rudimentary simulation experiments of synthetic living skin with morphogenesis characteristics were conducted in order to understand how to implement the principles and the rules of responsiveness, adaptability[10] and the parameters (Parametricism)[11] in the design stage of buildings skins. By elaboration and examination of these principles, a better understanding of their application in the biomimetic context of architecture will be achieved by means of more efficiency and effectiveness. This process involves developing simulations and modelling to derive rules from such principles. Most current building “skins” are quite static. Rather than being a bridge that permits the outside and interior to speak, several building skins nowadays serve to separate the inside from the outside with solely, if any, intermittent window openings.

As previously mentioned, this simulation concentrates on experimenting with the effect of the application of Biomimetic elements, established in this research, into three conventional and one unconventional shading. Additionally, this study claims the research is based on generic solid materials transparency and the translucency of materials was not taken into account; therefore, the material is a constant factor, and any material variation would produce a negligible impact on the solar gain calculation.

3.1.3.1 Case Studies

One of the regions with increasing interest in construction while having extreme environmental conditions in the summer is the Persian Gulf. The temperature of this region can rise up to 60 degrees in the summer (Pal and Eltahir, 2016). This research attempts to respond to the objectives in chapter one through comparisons of the original and evolutionary-generated skins of the following four towers located in the Persian Gulf region. Given the monotony of the building skins in these projects, the overall morphology of the skins will be incapable of responding to all part of the building that requires different criteria of view and solar radiation reduction. Early design explorations to improve the final design outputs are crucial in order to lower the construction and post-construction costs, as well as enable the static skin to be able to respond exclusively to a different part of the building. By focusing on the office floors of each case study building, an alternative formal configuration of the selected floors in relation to their skin form is addressed through the experiments presented in this research. This limitation of the study results in improving the efficiency, time-consuming, and quality of proposed design solutions.

[10] It is important to note that the word "Adaptability" in this context is not referring to dynamic façade systems (i.e. able to be mechanically reconfigured) but to an adaptive design process that results in a static, but highly differentiated design. This will be achieved via early design exploration method through predicting users behaviour and considering sunpath and solar radiation angle during the busies time of the day and hottest days of the year.

[11] Parametricism is a style within contemporary avant-garde architecture, promoted as a successor to post-modern architecture and modern architecture. The term was coined in 2008 by Patrik Schumacher, an architectural partner of Zaha Hadid (1950-2016) (Schumacher, 2010).

In other words, this part of the study highlights the significance of the adaptation of skin to extreme environmental conditions as well as the early-stage skin design exploration. Secondary evaluation mechanisms have been embedded into the evolutionary simulation to steer the evolutionary process toward generating such adapted formal attributes.

The PIF towers, Abu Dhabi Market Square and Al-hilal Tower, are protected from solar radiation by linear shadings, and Al-Bahr towers take advantage of dynamic cellular shadings. In the literature review chapter of this study, the downside of all linear shadings has been highlighted. The paragraph below is the outcome of the investigation into the Albahr towers' skin for the purpose of understanding the pros and cons of the cellular case study of this study.

PIF towers

A 385 m (1,263 ft) high skyscraper in Riyadh, Saudi Arabia, is known as the Public Investment Fund (PIF) Tower. It became Riyadh's tallest skyscraper in 2014 after construction began in 2010 and was completed.

The building's design was primarily focused on making it simultaneously functional and iconic. An irregularly shaped building site with numerous surfaces surrounding it placed restrictions on architects. This influenced the building's prismatic design, which has numerous diamond-shaped facets that enable the sun to be captured in several different ways. When developing this structure, which is anticipated to receive LEED Gold certification, the architects took Riyadh's hot and sunny climate into great consideration. Because of the transparency of the tower, the interior is open, and the workers have access to natural light. The extreme Saudi heat and light are moderated with a high-performance sun control system. The triple-pane unitized glazing's thermal efficiency is increased by

Figure 34 *PIF towers (Capital Market Authority Tower, Riyadh, Saudi Arabia, 2016)*

an exterior layer of fins, gantries, and perforated panels, which also provide shade. Together, these shading tools reduce internal cooling loads and solar gain, which lowers the need for HV AC.

Abu Dhabi Market Square

Four office towers frame the headquarters building: two at 31 stories and the other two at 37 stories located in Abu Dhabi, United Arab Emirates. The first full office floor of each building starts 34 meters above the ground level.

The project emphasized a sustainable design approach throughout. One of the main initiatives involved the environmentally responsive enclosure system that uses a mechanically ventilated cavity and a double-skin façade system over large portions of the office buildings. These elements help mitigate the 40 ºF interior-exterior temperature differential. The double-skin cavities run the entire height of the four office towers. Within the cavities, active solar shades track and adjust for the sun angle in order to provide optimal shading to the building's interior. Active lighting controls also help balance natural and artificial light. Because of these and other measures, the complex became the first integrated development in Abu Dhabi to be certified LEED-CS Gold.

Figure 35 Abu Dhabi Market Square (Abu Dhabi Global Market Square, 2019)

Al Hilal Bank Tower

This 24-story office tower is located on Al Maryah Island in Abu Dhabi, United Arab Emirates. With the best Class A office space available, the building is designed to draw top national and international businesses. With its effective, column-free floor plates, floor-to-ceiling glass, and the newest amenities and technology, the building fills a need in the expanding market. The podium contains retail space and a dramatic three-story transparent lobby to the north, with pedestrian arcades on the east and west. Three cubical masses sit atop the podium, stacked like shifted blocks. Designed to set the building apart from other towers on the island, these forms derive their interest from recessed corners that are offset from each other. In addition, the building's façade changes at the created voids to accentuate the shifted aesthetic. A spectacular three-story translucent lobby and retail space are located on the podium, which also has pedestrian arcades on the east and west sides. On top of the podium, three cubical masses are arranged in a jumbled fashion. These shapes were intended to distinguish the building from neighbouring island towers, and the forms are inspired by their offset recessed corners (Al Hilal Bank Office Tower, 2020).

Orange highlights draw attention to the gaps while emphasising the bank's identity both throughout the day and at night. The facade is built of an aluminium-and-glass curtain wall system with glass and notched metal spandrel components and vertical glass fins that accentuate the building's verticality and provide slight shadings (Al Hilal Bank Office Tower / Goettsch Partners, 2021).

Figure 36 Al Hilal Bank Tower (Al Hilal Bank Office Tower / Goettsch Partners, 2021)

The Al Bahr Towers

Towers, located in Abu Dhabi’s financial centre, have been constructed with the objective of creating a sustainable project for a region with hot and extreme climatic conditions. The building is comprised of two identical 145m tall towers with 26 stories each, and geometric patterns inspired by Islamic culture. Al Bahr towers are amongst many other buildings to employ methods of neutralizing the effects of extreme temperature rise in the region (Armstrong *et al*., 2013).

According to Arup Journal 2013, the main area of consideration in response to the environment in the case of Al Bahr Towers was the skin system, comprising the external kinetic panels to reduce the effects of the excessive solar radiation exposure on the building (Armstrong et al., 2013).

The mechanical movements of the skin have made it responsive to external conditions; however, on the other hand, this increases the cost of energy consumed by this system and, subsequently, its maintenance expenditures. Given the uniqueness of the skin system in this project, the overall morphology of the towers is comprising of two cylinders with having no other formal attributes rather than the applied skin to respond to the exposed excessive solar radiation.

The choice of glass material in the case of the Al-Bahr towers, in order to maintain a degree of freedom of view from inside to outside, is in fact another reason for the employment of such a skin system to block the excessive solar radiation as much as possible. This research tries to put forward an evolutionary design methodology that implies the importance of early design explorations of form and skin through which the adaptation to excessive solar radiation will be addressed from early design phases.

Figure 37 *The view from inside to the outside of the Al-Bahr towers (Al Bahr Towers, 2011)*

Figure 38 *The Al-Bahr Towers (Al Bahr Towers, 2011)*

The criticism regarding the implemented skin system in the Al-Bahr project to adapt to its environmental conditions is the reason that made this project to be selected as a case study with more potential room for deeper investigation and experiment in comparison to other case studies. The research that was conducted by Shady Attia (2018) has raised concerns regarding the sustainability of this project. Based on the result of Attia's surveys, 60% of the users are uncomfortable with the natural light that is received through the skin. Covering the buildings with glass material (to maintain the freedom of view from inside to outside) in the desert environment creates a challenging problem. The use of the kinetic panels is a response to a problem that was created by the glass façade initially. The mechanical movements of the skin have made it responsive to 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 the construction to 390 million euros. (Attia, 2018)

Species have developed formal characteristics to adapt to extreme environmental conditions throughout the course of their evolutions. Through investigations on species and the ways in which they adapt their forms and behaviours to their environment, the experiments presented in this study is going to explore alternative skin morphological configuration of the four selected buildings in relation to their skin in extreme environmental condition, i.e. the Persian Gulf region. This research aims to emphasise the formal configuration of architectural skin in their adaptation to their environment via early design explorations to improve the final design outputs. This is crucial in order to lower construction and post-construction costs.

3.1.3.2 Computational Platform

Evolutionary multi-objective optimization strategies have been utilised widely since the late 20th century as problem-solving methods. The work of Sewell Wright in the 1930s is the earliest instance of the application of evolutionary principles as optimization processes (Aedas, 2019). Midway through the 20th century, John Holland's Genetic Algorithms (GA) (Helbing and Molnar, 1995), Rechenberg and Schwefel's Evolutionary Strategies (ES) (Surowiecki and Silverman, 2007) and Fogel et al. 's Evolutionary Programming (EP) (Harvey, 2001) were developed independently from one another and led to the establishment of a unified field of evolutionary computation in the late 20th century (Skou, 2013).

Erns Mayr (1988) 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 (Mayr, 1988). Most widely used evolutionary algorithms, such as NSGA-II [12] (Bateson, 2012), 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

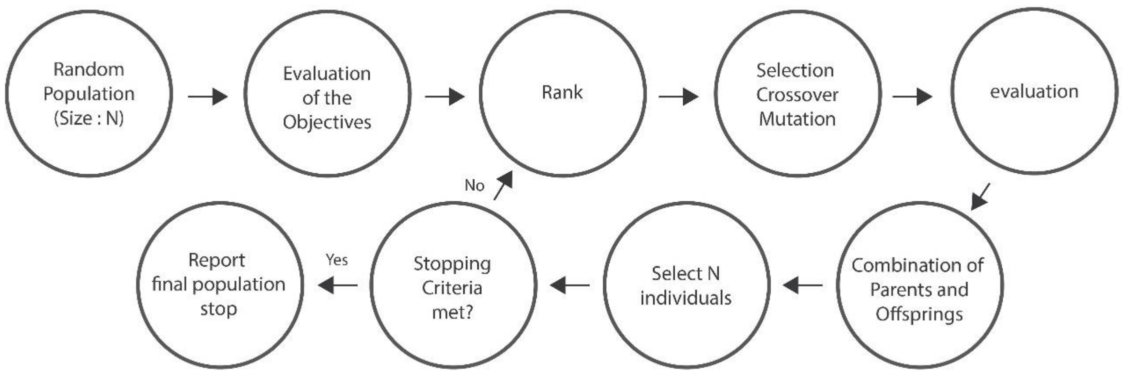


Figure 39 *NSGA-II algorithm pseudocode.*

[12] Non-dominated Sorting Genetic Algorithm-II; an standard Evolutionary algorithms for Multi-objective optimisation purposes

variations and evaluation of the solutions on their objective performance. It ends by selecting a group of solutions based on a predefined selection mechanism (Turner, 2002) (Figure 39).

Despite the large number of evolutionary optimisation algorithms that are now in use, they may be classified into either Single-Objective Evolutionary Algorithms (SOEA) or Multi-Objective Evolutionary Algorithms (MOEA). When addressing issues with a single objective, the former employs evolutionary problem-solving approaches; when tackling problems with multiple competing objectives, however (if the objectives are not in conflict, the problem may be addressed using an SOEA), the latter employs the same ideas. The main distinction between these two categories of algorithms is the result, as SOEA often produces a single solution that solves the problem's solitary issue. However, due to the competing aims guiding the simulation, there is not a single best answer in the MOEA. A solution that works best for one goal may not be the best choice for another. In order to try to optimize for each goal separately within the same algorithmic run, the MOEA generates a solution set (Deb, 2006).

Through the use of variation and selection techniques, the algorithmic application of evolutionary concepts in multi-objective optimisation schemes mimics the behaviour of its natural equivalent (Pareto front solutions). Nevertheless, for their application to be successful, it must produce a wide range of solutions in a reasonable amount of time. Luke Sean (2013) claims that a search and optimization method that is both exploratory and exploitative should be balanced in the algorithm configuration. The first one relates to a sufficient level of mutation and crossover to enable a varied population of candidate solutions, and the second one refers to the effective selection and variation techniques that guide the algorithm towards an optimal solution set within an acceptable amount of generations (Luke, 2013)

The advantages of using evolutionary concepts in design were investigated by architects and planners beginning in the second half of the 20th century (Batty, 2013; Coates, 2010; Weinstock, 2010b; Marshall, 2008; Steadman, 2008b; Frazer, 1995). The design issues under investigation in the context of the presented study involve several sets of competing objectives and a broad search area. In order to execute the evolutionary simulations, the MOEA is the primary approach used in this situation. Additionally, evolutionary simulation makes it easier to include biological homeostatic principles into its algorithmic loops by facilitating a responsive generative framework as a design model (Kaviani and Showkatbakhsh, 2020; Showkatbakhsh and Makki, 2020).

Although research by Wortmann et al. (2017) questions the effectiveness of evolutionary algorithms, specifically genetic algorithms, in addressing a single-objective issue because of several competing objectives and a wide range of potential solutions, MOEA is the approach used in this study (Coello, 2006; Branke et al., 2008; Deb, 2008; Luke, 2013; Rothlauf, 2011) Furthermore, compared to other optimisation techniques used in the design discipline, multi-objective evolutionary optimisation strategies are more in accordance with the evolution's biological principles (abstracted in section 2.1.2.5).

The use of multi-objective evolutionary algorithms has grown both in academia and industry recently as a result of advancements in computing power and general accessibility to design platforms that enable algorithmic implementations. One of the well-known platforms, Grasshopper, created by (Rutten, 2013), allowed the use of unique algorithms in the design process, including evolutionary algorithms. Users can perform evolutionary simulations using one of the several evolutionary solvers available in the Grasshopper platform. Among the most well-known and frequently used evolutionary solvers to date are Galapagos, developed by Rutten in 2010; Octopus, developed by Vierlinger in 2013. Biomorpher, developed by Harding and Branst in 2017; Design Space Exploration, developed by MIT in 2017; and Wallacei (Makki et al., 2019). With the exception of Galapagos, which is a single-goal optimisation, the others are multi-objective optimisation engines. Wallacei, in the presented experiments, is used as the primary evolutionary solver due to a number of factors, including access to the simulation's whole evolutionary history, as well as live and dynamic statistical representations of the performances of the solutions, and the provision of a comprehensive collection of methods for analysis and selection that use machine learning algorithms to reduce the population.

Evolutionary optimisation techniques have become more prevalent in recent years among academics and practitioners in the fields of architecture and design. Ayman Hassaan (2016), in his research, looked at the early geometric formations of the skin to examine the use of evolutionary optimisation in the design phase (Mahmoud and Elghazi, 2016).

Yun Kyu Yi implemented NSGA-II algorithm in his investigations of optimising building facades (Yi, 2019). Machairas et al. used the genetic algorithm to address a set of conflicting objectives in the early design phase of a building (Machairas et al., 2014). 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 (The Living, 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, 2015). In this context, heat [13]received by solar radiation is the parameter by which homeostasis will be maintained and monitored through the insertion of secondary evaluation mechanisms as the algorithm loops into the evolutionary simulation (Figure 5). With a similar goal but a different algorithmic approach to the experiments presented in the study (Kaviani and Showkatbakhsh, 2021), this research investigates the application of homeostatic feedback mechanisms into the evolutionary simulations to generate adaptive forms.

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 (2015) 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.

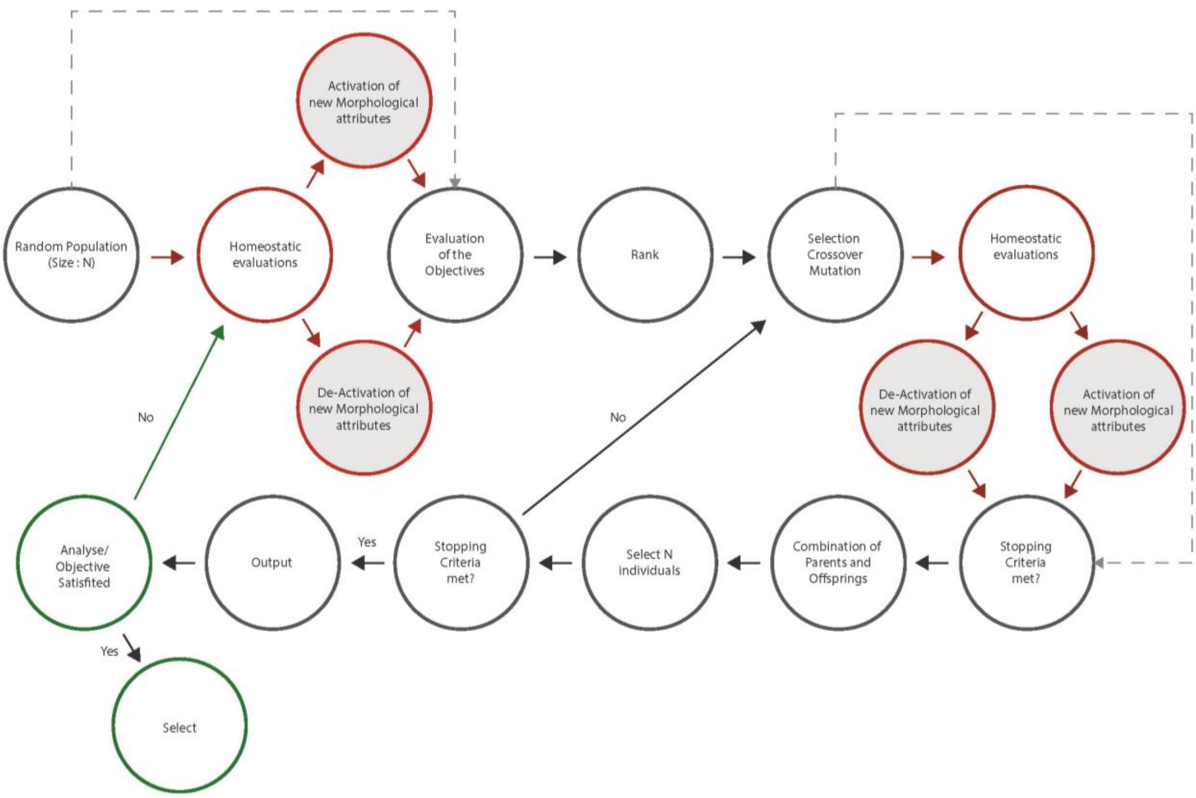


Figure 40 *The modified evolutionary simulation workflow with two secondary evaluation mechanisms. The red squares show the modified stages. The green square shows the added step on the application of evolutionary simulation in design using Wallacei.*

[13] In the context of this study, solar radiation is taken as the only way by which heat can be exchanged. Thus, the primary aspect of the conducted experiment is the significance of the building skin's shadings in the adaptation to excessive solar radiation through evolutionary simulation with homeostatic feedback mechanisms.

4 Experiments, Results & Analysis

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 the excessive solar radiation of the Persian Gulf region. In the context of this research, the seasonal solstices and equinoxes (21st of June, September, December and March) are considered the dates on which solar radiation is calculated and studied. This research, through comparisons to the original skins of the PIF towers, Abu Dhabi Market Square, Al-hilal Tower, and Al-Bahr Towers, highlights the significance of adaptation of skin to extreme environmental conditions. In each case study, the original skin of the building will be completely modelled, and the skin will be exposed to solar radiation during selected dates in order to measure the skin's performance in terms of 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. A set of genes, concluded from the studies conducted on the significance of morphology on the adaptation of species (section 2.1.2.5), inserted into the genome to enable the modifications should simulation favour them (table 3 & figure 43). The experiments of this study fall into two phases with different design problem-solving approaches that will be elaborated on in the following sections.

4.1 Experiment Setup (Phase I)

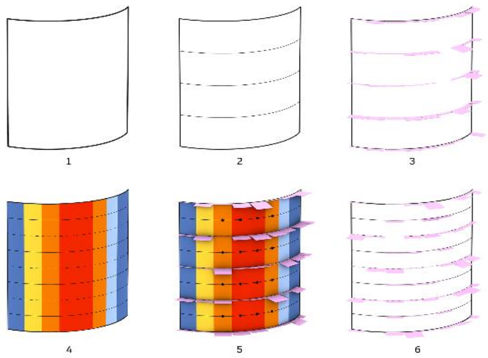
Throughout the evolutionary simulations of this research, four types of building skin on four selected case studies will be evaluated (both statistically and morphologically) to highlight any emergent behaviour among the evolved solutions at either the different levels or surfaces of a building across multiple generations. The experiment will present these behavioural attributes by analysing individual solutions extracted from different generations throughout seven evolutionary simulations. Their performance in adapting to the excessive solar radiation of the region based on a set of measurement criteria will be compared with the original skin of each case study. The Abu-Dhabi Market, Al-Hilal Tower and PIF tower simulations will be based on the evolution of their original shape of skin (horizontal, vertical and crossed; explained in Figure 41). The study over Al-Bahr towers in this research is more in-depth in comparison to the other three case studies as the skin is more complex, and there are more modelling, survey and analysis data available for this project than in other case studies. Therefore, both cellular and linear types of skin are going to be experimented and tested in this project (described in figures 53 & 54). Hence, four out of seven experiments presented in this study will explore alternative skin morphological configurations of the Al-Bahr towers in relation to their original skin.

Linear Skin: Horizontal

Will be applied to:

Abu-Dhabi Market

Al bahr Towers

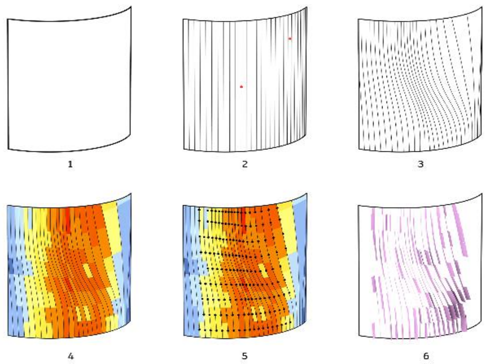


Linear Skin: Vertical

Will be applied to:

Al-Hilal Tower

Al-bahr Towers

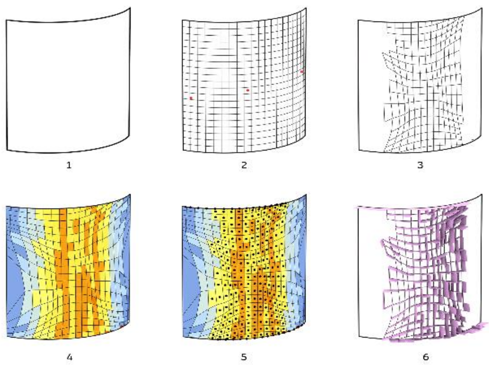


Linear Skin: Crossed / Eggcrate

Will be applied to:

PIF Tower

Al-Bahr Towers



Cellular Skin: N-gon/hexagon

Will be applied to:

Al-Bahr Towers

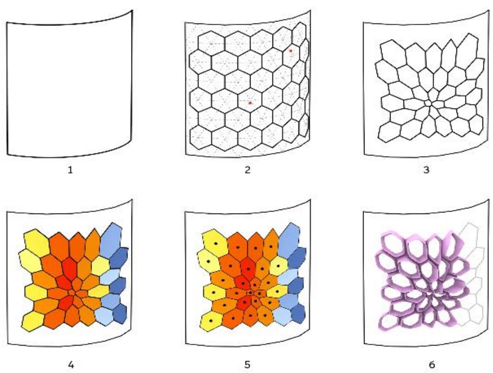


***Figure 41** Basic Illustration of the development of each type of skin in the evolutionary design experiment as well as the types of shadings used in the evolutionary design platform (Phase I). The red dots are attractor units that can be spread throughout the building surface area to change the density of the skin cells or shadings*

4.1.1 Homeostatic Feedback Mechanism

Two secondary feedback mechanisms are added to the evolutionary simulation to steer it towards generating the extra set of adaptive formal attributes within the phonotypes. They are called homeostatic mechanism A and homeostatic mechanism B (figure 42).

*Homeostatic Mechanism A (**H-M-A**)* directs the simulation to generate the skin system on the buildings should a specific condition be met. Homeostatic regulatory mechanism in the algorithm can be identified into its three main elements, and they are as follows (table 1):

a) ***Set point***: solar radiation of more than 3.5 kWh/m^2 exposed on the building's surface with no skin is the threshold, after which a responsive feedback mechanism will be activated in order to counteract the deviation. (The figure of 3.5 kWh/m^2 was chosen as a design input and excessive radiation threshold; this number can be modified accordingly in the other scenarios based on the location.

b) ***Receptor:*** Building skin has been created algorithmically, allowing for the evaluation of the solar radiation on the building surfaces.

c) ***Effector:*** if the amount of solar radiation exceeds 3.5 kWh/$m^{2,}$ a new morphological attribute will be activated on the exposed surfaces and modifies the existing shadings. (Table 3).

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

Table 1 *Homeostatic Mechanism A (H-M-A)*

Functions and Variables	Description
X	*The generated phenotype in each iteration*
F ()	*Receptor. The Function that returns the parts of the phenotype that receive solar radiation of more than 3.5kwh/m^2*
G ()	*Effector. The Function that applies the morphological changes onto the phenotype*

*Homeostatic Mechanism B (**H-M-B**)* affects areas of the buildings with exposure to higher solar radiation in comparison to H-M-A. However, in a similar fashion, this regulatory mechanism in the algorithm can be simplified to its three main elements, and they are as follows (table 2):

a) ***Set point***: 4 kWh/m^2 of the solar radiation on the building skin is the threshold after which a responsive feedback mechanism will be activated in order to counteract the deviation (4kwh/m^2 was chosen as a design input and excessive radiation threshold, this number can be modified accordingly in the other scenarios based on the location).

b) ***Receptor:*** Building skins have been created algorithmically, allowing for the evaluation of the solar radiation on the building surfaces.

c) ***Effector:*** if the amount of solar radiation exceeds 4 kWh/m^2, a new set of shading with new morphological attributes will be activated on the exposed building surfaces. (resulting in increasing the density of the shading in the selected areas)

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

Table 2 *Homeostatic Mechanism B (H-M-B)*

Functions and Variables	Description
X	*The generated phenotype in each iteration*
K ()	*Receptor. The Function that returns the parts of the phenotype with no skin that receives solar radiation more than 4 kWh/m^2*
H ()	*Effector. The Function that applies the morphological changes to the phenotype*

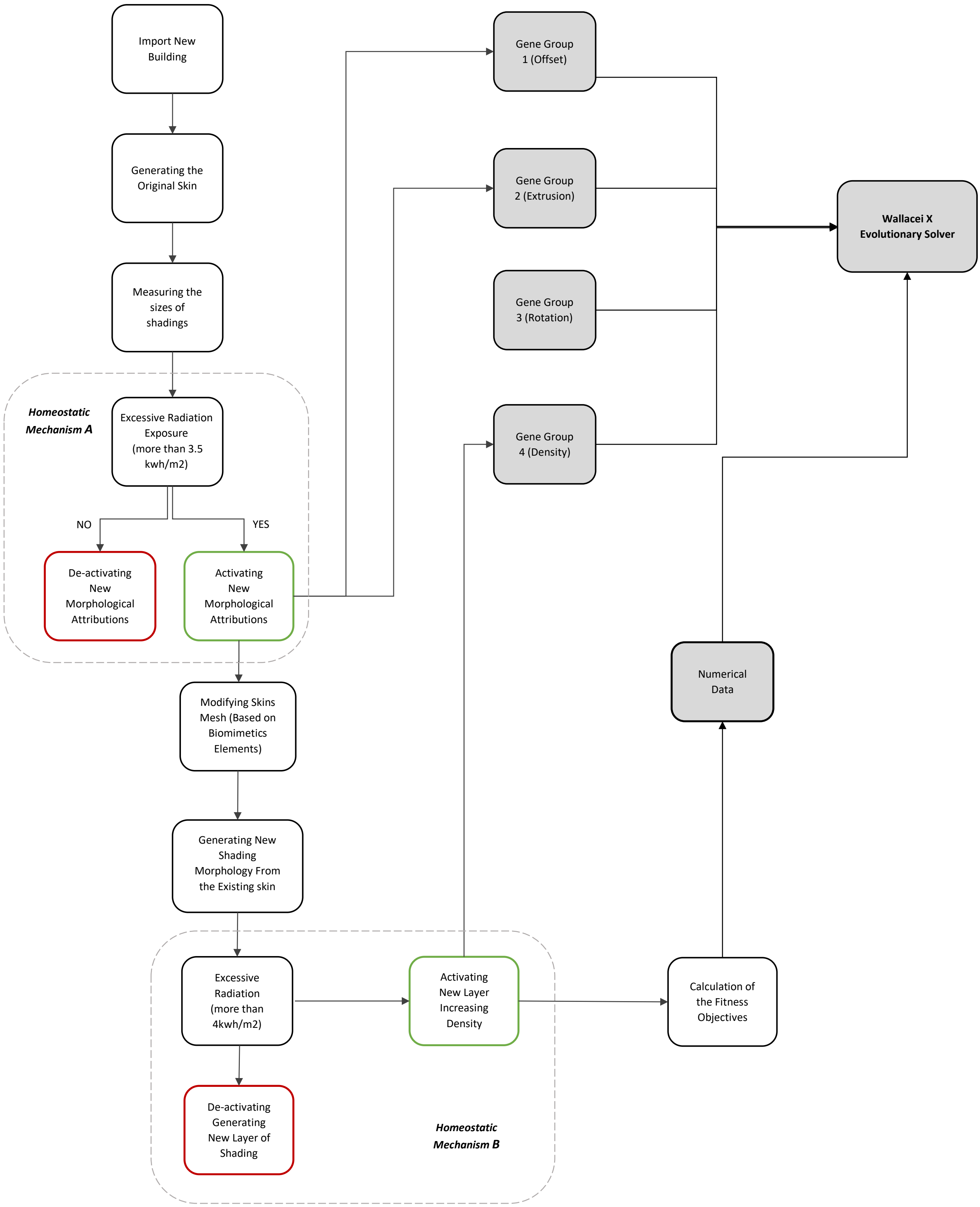


***Figure 42** The pseudocode of the design problem within which the evolutionary simulation will be operating.*

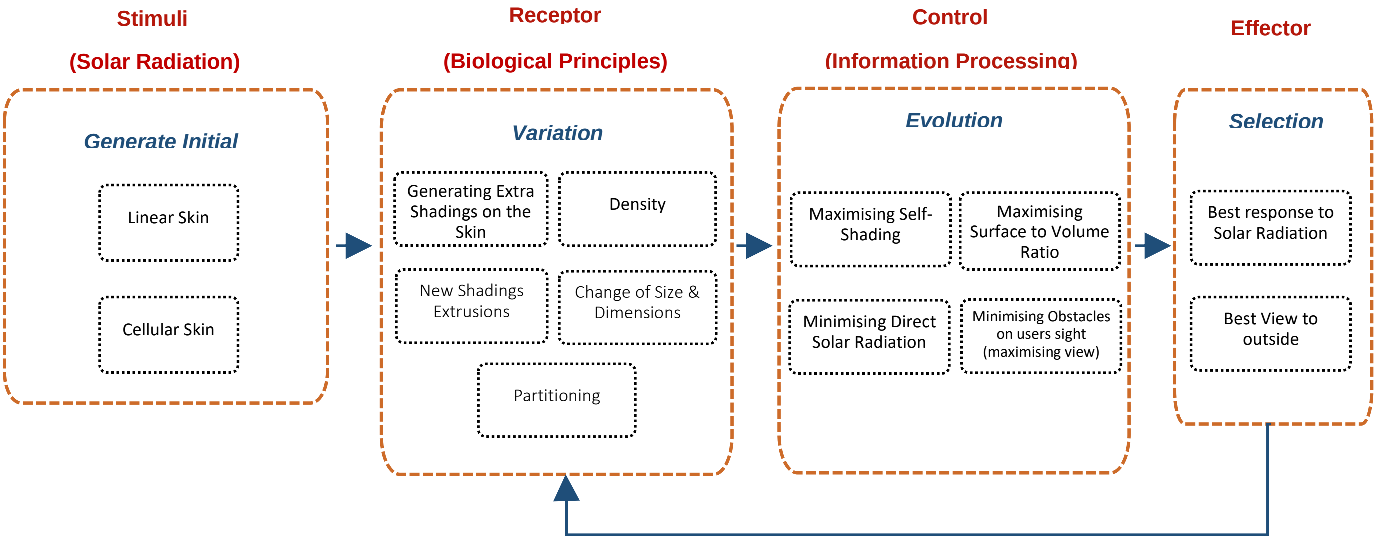


Figure 43 *Homeostasis Feedback Loop In relation to the Evolutionary Algorithm that generates skin*

4.1.2 Selection of the Fitness Criteria

The evolutionary simulation was developed to generate a building skin in Abu-Dhabi and Riyadh for the four different towers to optimise for the following Fitness Objectives (FO):

a) *FO1*: To increase the shadow on the buildings by *self-shading* mechanisms (Figures 44 & 45)

b) *FO2*: To increase the view from the inside of the buildings towards the outside (figure 46)

Each of these objectives was formulated to direct the evolutionary simulation toward the emergence of the formal attributes (table 3 & figures 47 to 54) 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.

A set of genes was introduced to the primitive skin (table 3 & figures 47 to 54) to enable the necessary transformations to occur in the phenotypes to increase the shadow on the buildings by a self-shading mechanism. By increasing the self-shading of the building skin, the morphology will be essential in preventing solar radiation from hitting the object. As a result, it will help to lower the amount of energy needed for cooling systems during hot weather. The sample points populate the geometries to efficiently calculate the self-shading objective (Pa). 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).

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

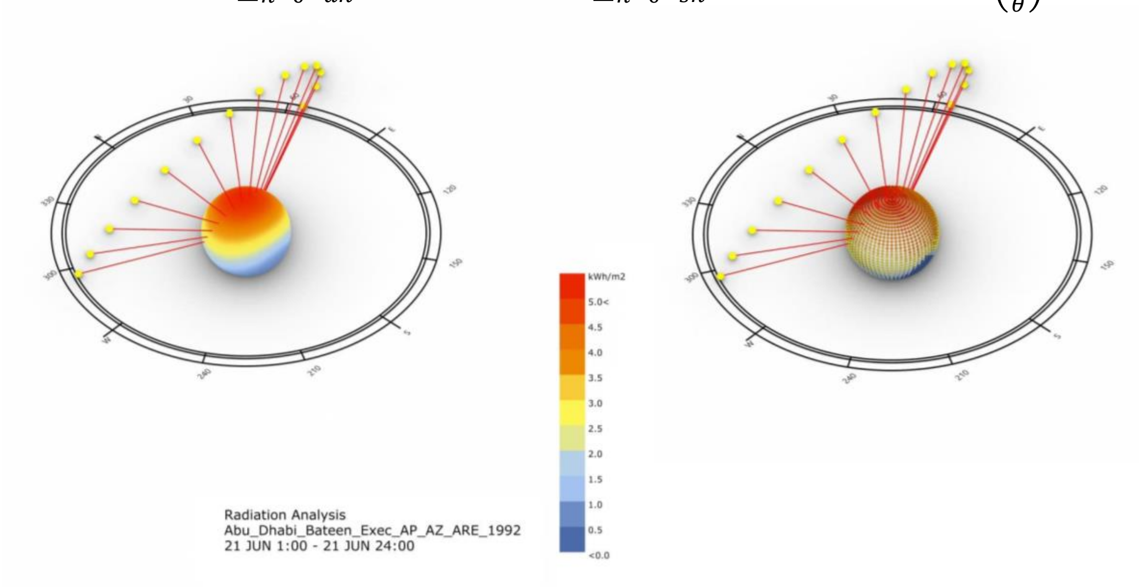


Figure 45 *The Illustration of sun radiation application over the building*

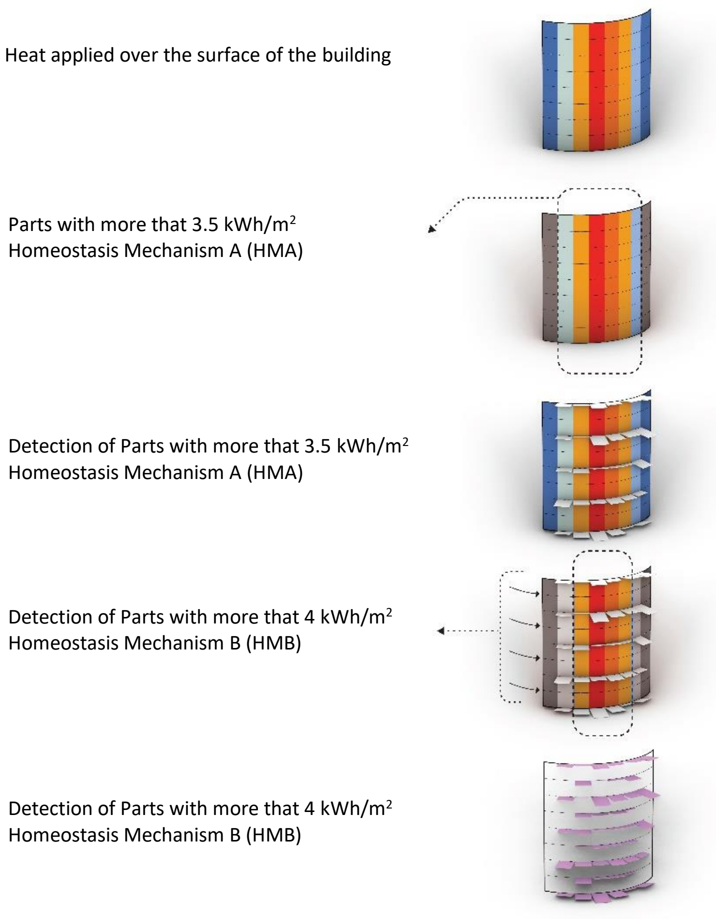


Figure 44 *The grouping technique inspired by geranium plant stem for the process of activation of HMA & HMB over the skin during the optimisation*

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 second objective is introduced to the evolutionary simulation to increase the view from inside to outside.

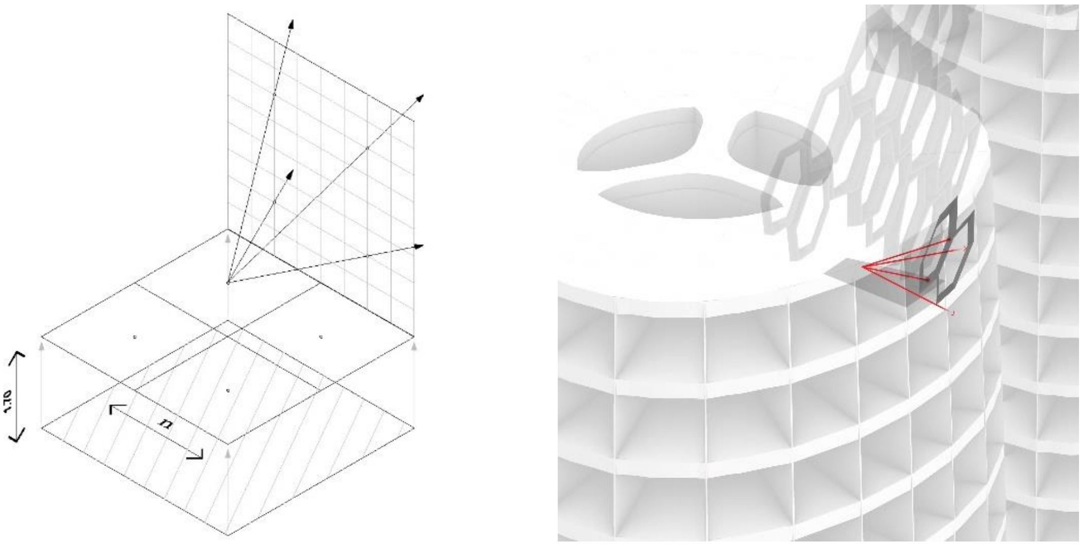


Figure 46 View Analysis Method

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 46. 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[14].

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

Given the complexity of the design problem, the experiment was limited to 10 individuals per generation with a total number of 500 generations (in total, 5000 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.

[14] 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)

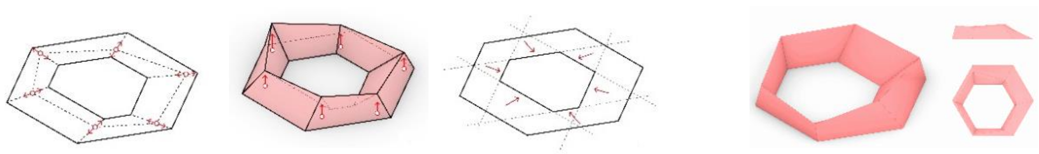
4.1.3 Genotypes and Phenotypes and the Development of the Skin:

The illustration of the skin development below is also available in an animated gif file format at: https://drive.google.com/drive/folders/1zEtwqAz4HfTFDBM2wfbKZHQZOHYd4z00?usp=sharing

Table 3 *This table shows the selected bio-inspired elements (based on the mind map) that have become the genes of the phenotypes in the evolutionary simulation*

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

1 2 3



4

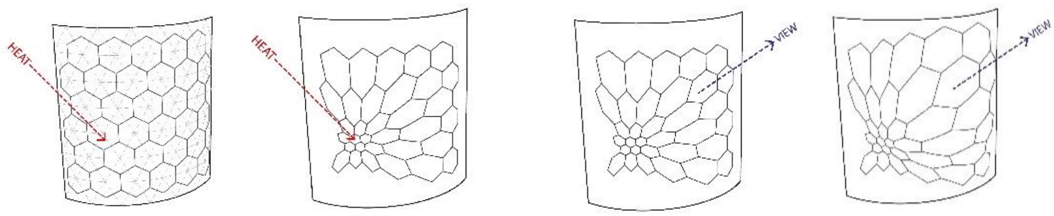


Figure 47 *Illustration of an example of genes morphological representation of proposed cellular skin*

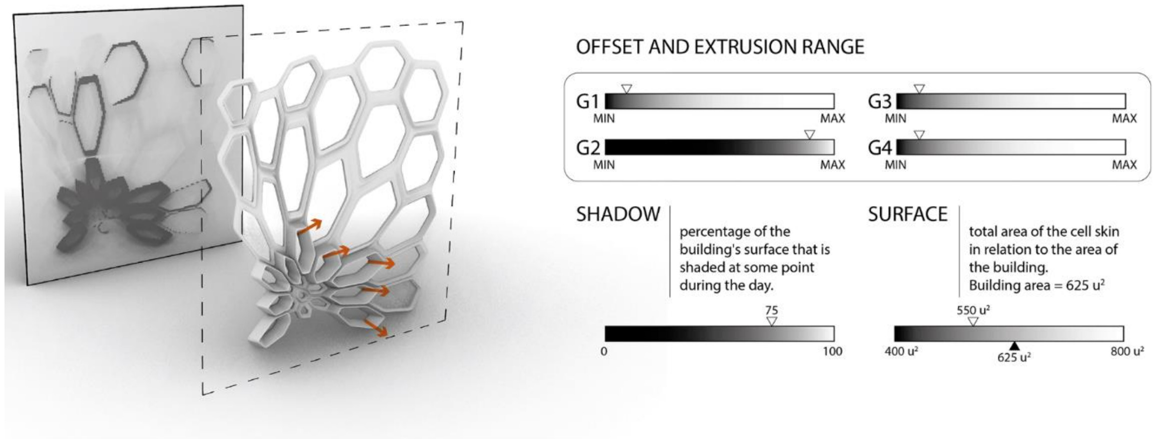


Figure 48 *The Illustration of the effect of the genes' modification on self-shading of the façade and by increasing surface to volume ratio. (Based on the grouping technique of geranium plant stem)*

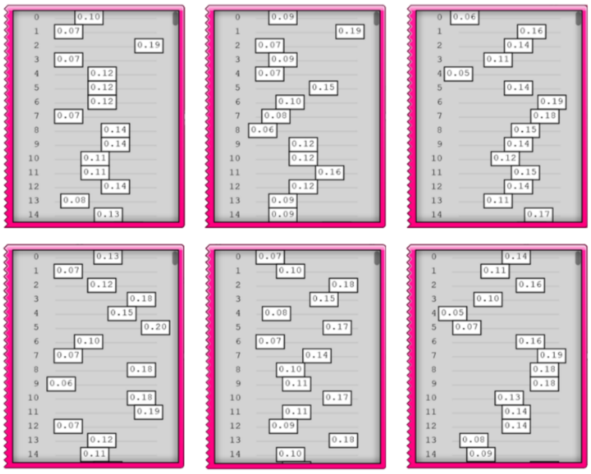


Figure 49 *Gene group 1 (offset) controls the selection of the algorithm that generates offsets for shadings (HMA)*

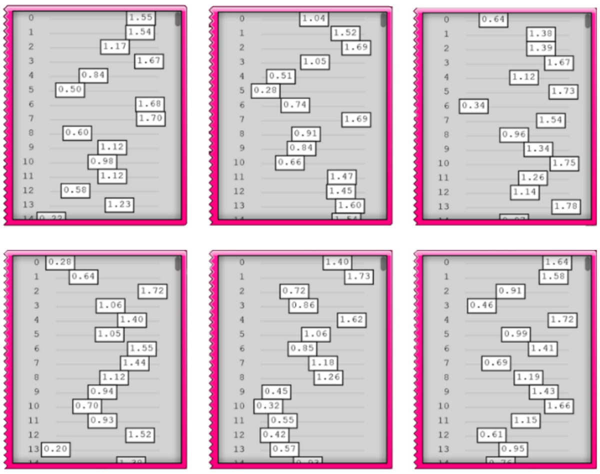


Figure 50 *Gene group 2 controls the morphological changes that generates and changes extrusions of the shadings which is part of the HMA and HMB.*

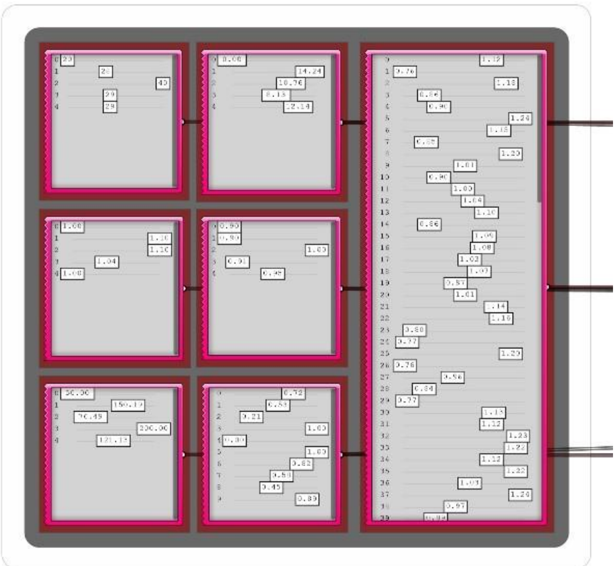


Figure 52 *Gene Group 3 controls the density of the shadings panels and cells. (Part of the HMA)*

Figure 51 Gene group 4 controls the morphological changes that generates and changes extrusions of the shadings which is part of the HMB.

The figures below demonstrate the development process of cellular skin and linear skin:

Cellular Skin

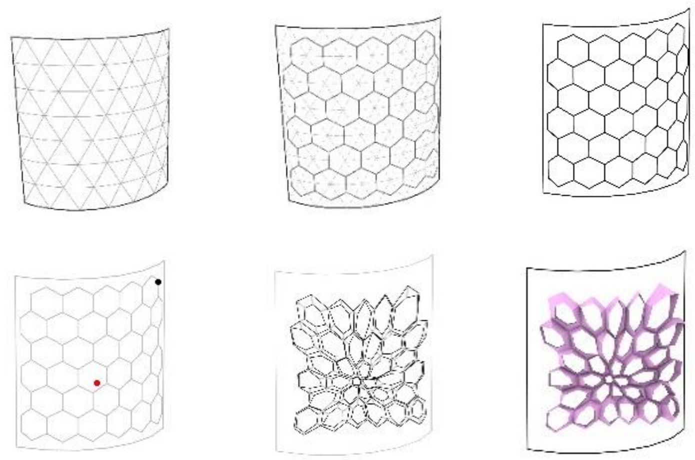


Figure 53 *Cellular Skin: Cellular skins can have different density of cells depending on the surface they are placed. In this instance, the red dot produces more density and black dot generates less density of cells.*

Linear Skin

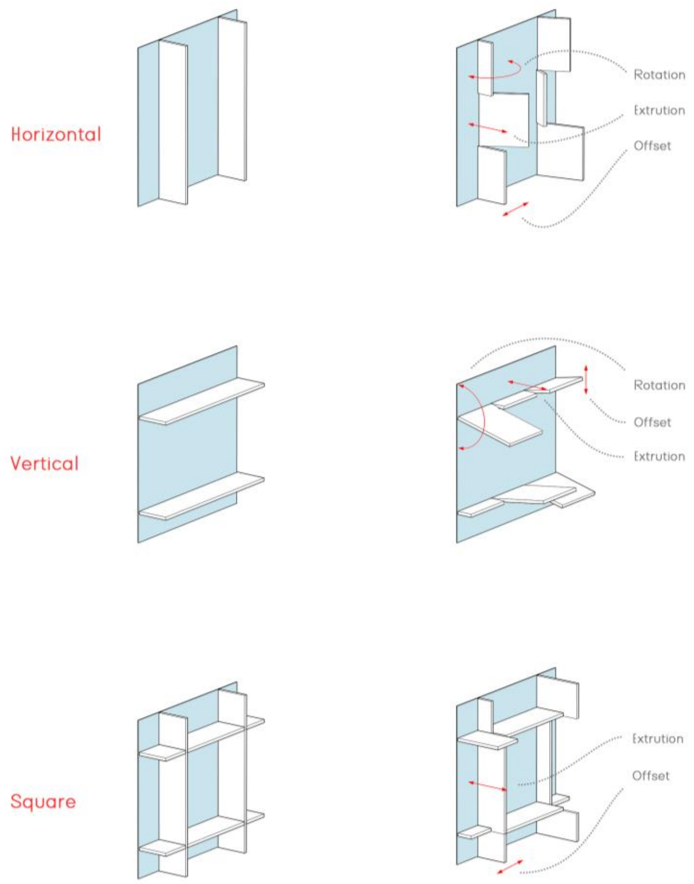


Figure 54 *Linear Skin, linear shadings can have different angles, length and arrangements*

4.1.4 Optimisation Mechanism

In addition to the analysis of the entire simulation for each case study, the best phenotypes were selected among the 5000 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. To select a set of candidate solutions in the multiobjective evolutionary algorithm while limiting the user's preference is a challenging task. To compare a wide range of solutions to the case studies' original skins, the selected solutions are the best option for each of both fitness objectives. As the view and the thermal comfort (fitness objectives) may contradict each other, the selected solution is the relative difference between the best fitness rank of each fitness objective (the solutions which address the fitness objectives equally). They also have the lowest average fitness rank amongst 5000 solutions (for further description of the selection strategies, please refer to (Makki et al., 2019).

To study the selected individuals thoroughly, each solution is accompanied by a full Wallacei analysis of their fitness performance independently and relative to the entire simulation. This is completed by an illustration of the morphological properties of each solution which can be seen at https://vimeo.com/512950848 for the cellular skin proposal of the Al-Bahr towers case study. 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? According to the annual maximum solar gain in Abu-Dhabi (Bankable solar data for better decisions, 2019), 6.3 KwH/m2 is the maximum solar gain per day in a year. Since neither the case studies nor the selected solutions will receive this much solar radiation (without considering the roofs), the figure 3.5 KwH/m2 is selected in this research to conduct a meaningful comparison between the case studies (with original skin) and the selected solutions (proposed and alternative skins). This analysis demonstrates how well the evolved morphological attributes of the phenotypes obstruct the solar radiation[15] exposed to the building surfaces compared to the case studies.

b) How much the evolved skin system obstructs the view from the inside to the outside of the buildings? Increasing the view as a fitness objective was introduced to the simulation to ensure the evolved skin contributes to the obstruction of solar radiation while maintaining a

[15] The Evolutionary Design Fitness Objective 1 for solar radiation has been facilitated via occlusion hits (occlusion component) in Grasshopper 3D software. And the analysis of this process over the proposed case studies in the following next pages of this section is done via ladybug plugin of Grasshopper 3D (Ladybug Tools. 2019). This has been done to have more assurance that the method used for optimisation process and the data produced from this simulation are valid.

degree of freedom of view from inside to outside of the buildings. In order to conduct a meaningful analysis between the selected solutions and the case studies, the only obstructing geometry that was counted in the calculation of the view rays from inside to the outside is the frame of the skin systems in both cases (case studies and selected candidates). The materiality, form, and function of the panels inside the frames have not been explored in the context of this research; these elements have been marked as further studies for exploring this subject further.

c) In all case studies and solutions, the only floors selected in terms of function are the office floors. This focused action results in more accurate data and increases the reproducibility of the experiment. In other words, any other function and unselected floor in the case studies can be optimised via the same method.

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 layer of skin) was triggered selectively (based on the fitness criteria and solar radiation intensively). The percentage of surface area for each of the case study proposed solutions that receive solar radiation more than the threshold is less than the case studies' original skin. All the selected solutions successfully created pockets of shadow on exactly the surface areas of the towers, which were exposed to excessive solar radiation that facilitated indoor office activities, an attribute that is missing in the case studies. The selected solutions hold advantages in facilitating the view from the inside to the outside of the buildings when compared to the case studies (Thorough analysis from section 4.1.4.1 to 4.1.4.7).

The evolutionary simulation used in this experiment is built using the multi-objective Non-Dominated Sorting Genetic Algorithm II (NSGA-II) developed by Deb. et al. (Deb et al., 2000). The simulation is conducted, and the results are extensively analysed using Rhinoceros3D, Grasshopper3D, and its plugin Wallacei (Makki et al., 2019). The following values were entered into the evolutionary simulation's algorithm parameters: (Table 4). (Please see (Makki et al., 2019) for an explanation of the terminology used in the simulation).

Wallacie evolutionary optimisation plugin was employed to run simulations aimed at achieving the best-performing building skin designs based on evolutionary principles. By utilising this plugin, the research tapped into the potential of genetic algorithms to optimize the building skin's performance in response to solar radiation.

Additionally, the Pedsim plugin for Grasshopper was utilized for agent-based modelling, enabling the investigation of pedestrian behaviour and its impact on building skin performance. Through agent-based simulations, the research gained valuable insights into how biomimetic building skins can enhance user comfort and experience while interacting with the architectural environment.

In the next section (4.2), the combination of Rhino 3D, Grasshopper, Wallacie, and Pedsim will play a pivotal role in facilitating a robust and comprehensive research methodology, enabling the exploration of biomimicry's potential in revolutionising building skin and facade design. These tools were chosen for their specific purposes, offering sophisticated parametric modelling, evolutionary optimisation, and agent-based simulation capabilities, which proved instrumental in achieving the research's objectives.

Table 4 Phase 1: Evolutionary Design Simulation Parameters

Parameter	**Short Description**	**Value**
Generation Size	*Number of individuals per generation*	10
Generation Count	*Number of generations in the simulation*	500
Crossover Probability	*Percentage of solutions that reproduce in each generation*	0.9
Mutation Probability	*The 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

The following pages comprise a series of illustrations[16] 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 55 to 96).

Please visit https://vimeo.com/manage/videos/512950848 to view the entire process in the design evolution of one of the case studies (the Albahr towers), as well as the new skin during the optimisation simulation.

[16] All design models for the case study buildings presented in this thesis were created by the candidate. The dimensions and specifications of the models were based on the information available from the construction companies, including Arup (Al Bahr Towers, 2011 and Armstrong et al., 2013). While every effort has been made to ensure accuracy, it is acknowledged that the models may not perfectly resemble the as-built facilities. However, the validity of the simulations is not compromised, as the primary purpose of the simulations was to compare the shading type of the buildings with their evolved versions. Any deviations in accuracy do not hinder the research's core objectives or conclusions.

Abu-Dhabi Market, Horizontal:

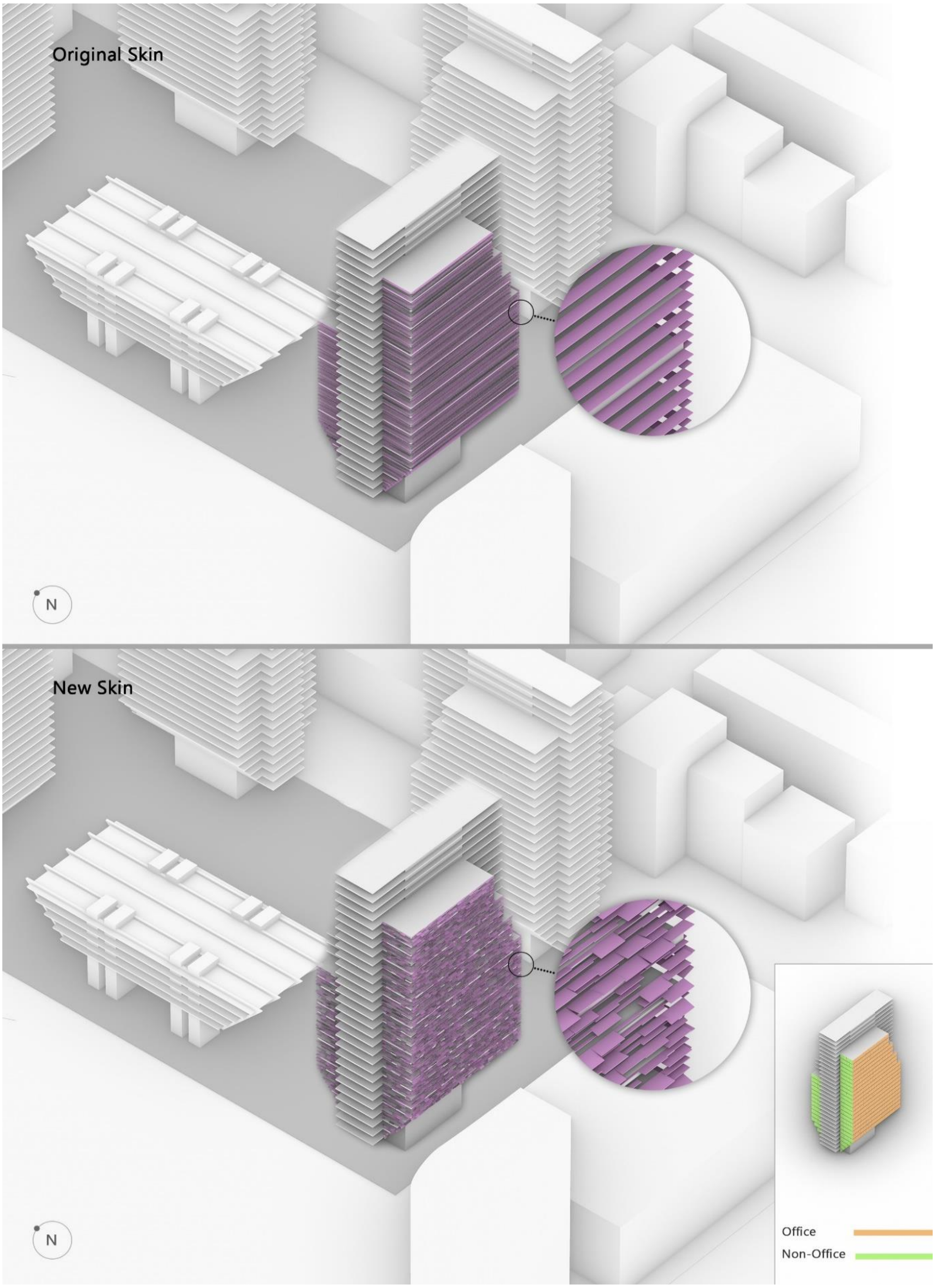


Figure 55 *Abu-Dhabi Market, Horizontal Skin (Before and After)*

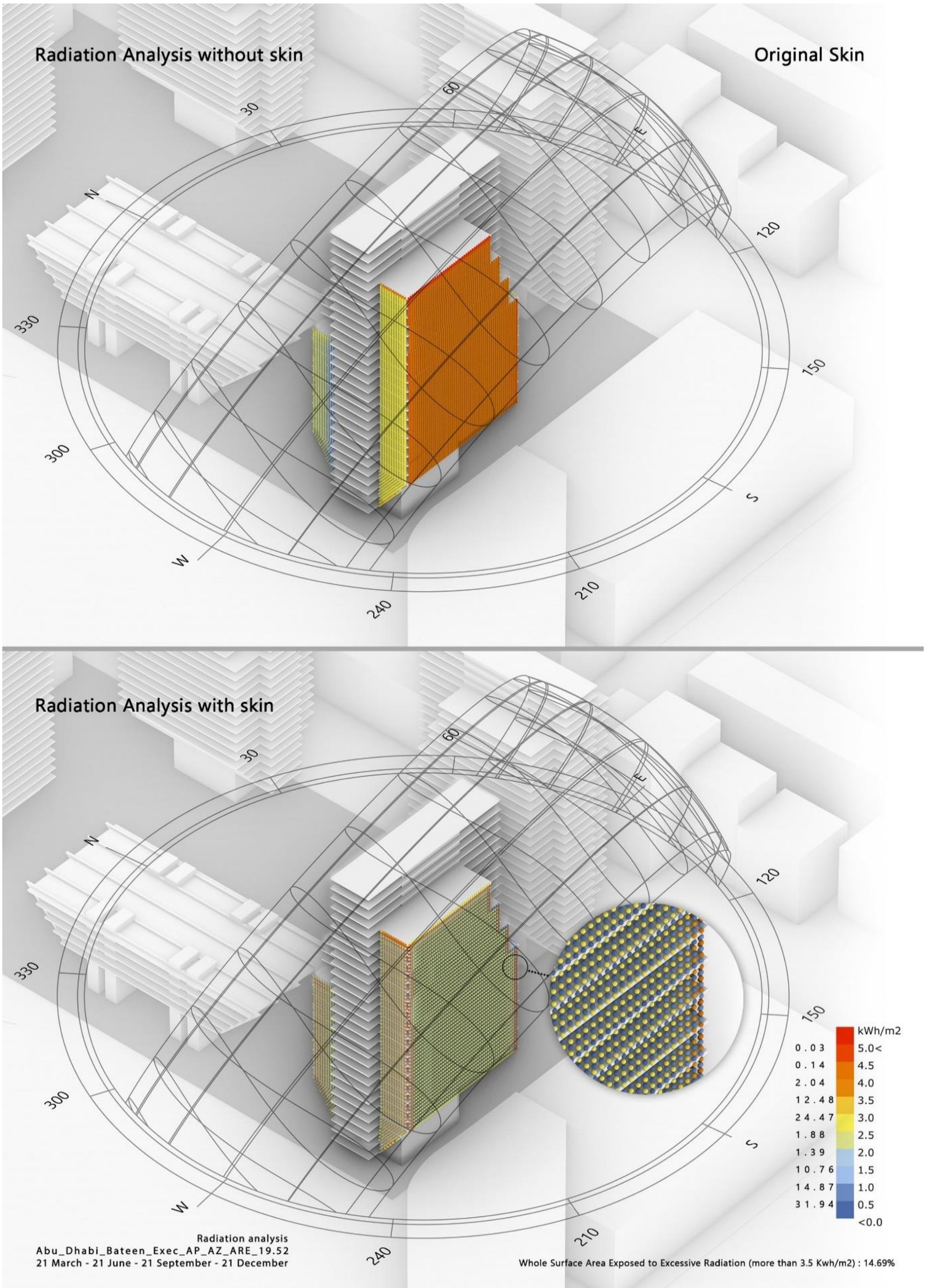


Figure 56 *Radiation Analysis of Abu-Dhabi Market with the original skin*

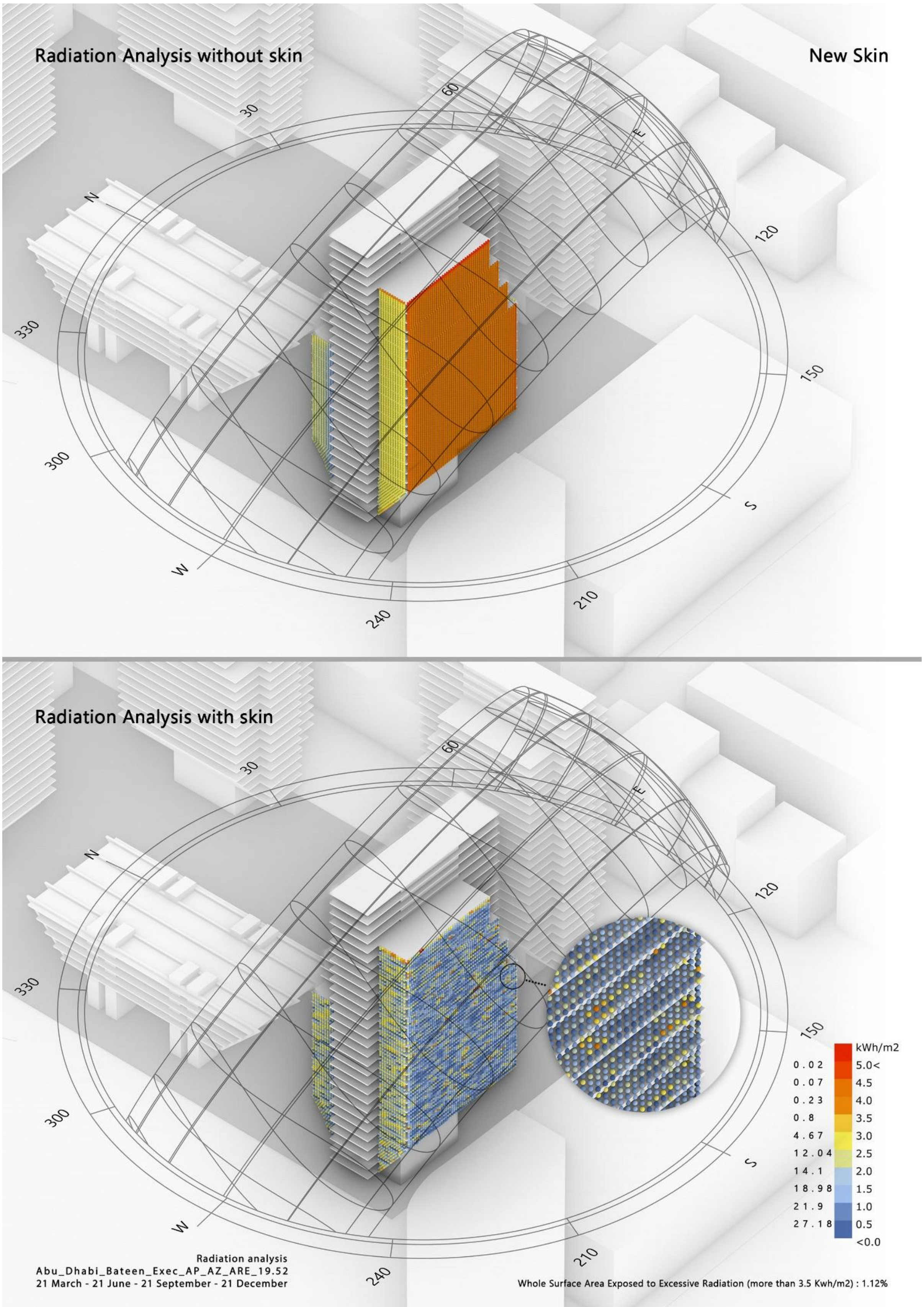


Figure 57 *Radiation Analysis Abu-Dhabi Market with the evolved skin*

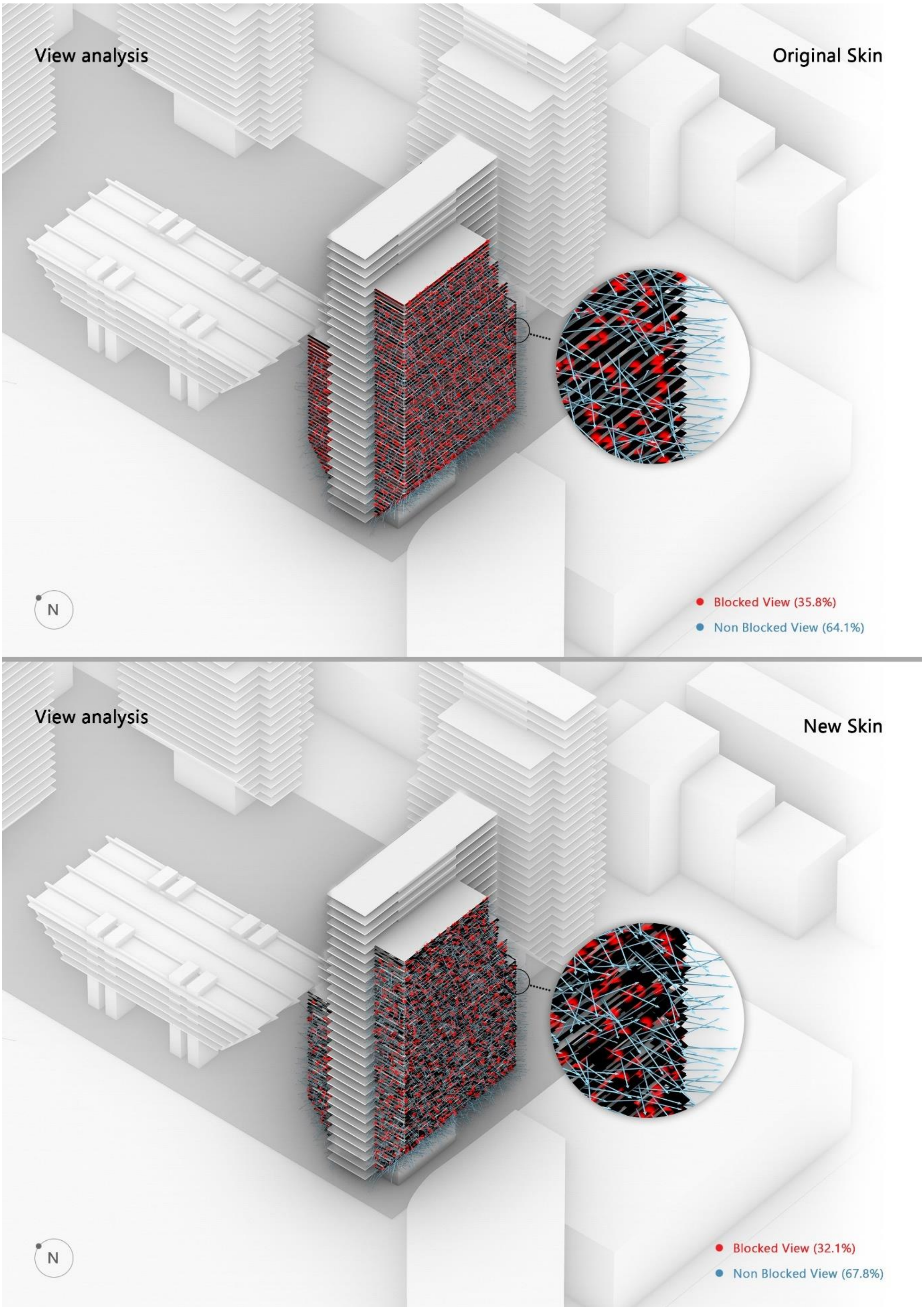
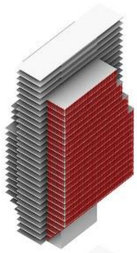


Figure 58 *View Analysis Abu-Dhabi Market*

Evaluation and Results: Abu Dhabi Market

Original Skin

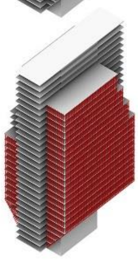


Office

% of whole surface area effected by radiation intensity		(KWh/m2)	View
0.13		5	
17.6		4.5	
8.48	=29.62	4	
3.41		3.5	
3.16		3	Office
0.34		2.5	
10.33		2	67.88%
20.48		1.5	
20.23		1	
15.84		0.5	

Other Places

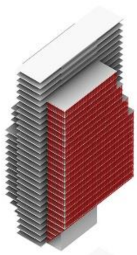
% of whole surface area effected by radiation intensity		(KWh/m2)	View
0.04		5	
0.19		4.5	
2.76	=13.55	4	
10.56		3.5	
30.3		3	Other places
1.05		2.5	
1.03		2	63.21%
9.76		1.5	
11.91		1	
32.4		0.5	



Overall

% of whole surface area effected by radiation intensity		(KWh/m2)	View
0.03		5	
0.14		4.5	
2.04	=14.69	4	
12.48		3.5	
24.47		3	Overall
1.88		2.5	
1.39		2	64.15%
10.76		1.5	
14.87		1	
31.94		0.5	

New Skin

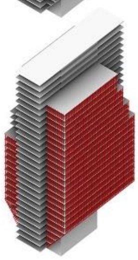


Office

% of whole surface area effected by radiation intensity		(KWh/m2)	View
0.06		5	
0.03		4.5	
3.07	=11.61	4	
8.45		3.5	
13.71		3	Office
8.83		2.5	
11.15		2	74.06%
7.98		1.5	
17.5		1	
29.21		0.5	

Other Places

% of whole surface area effected by radiation intensity		(KWh/m2)	View
0.02		5	
0.09		4.5	
0.31	=1.5	4	
1.08		3.5	
4.38		3	Other places
11.27		2.5	
13.95		2	64.51%
20.37		1.5	
25.53		1	
23		0.5	



Overall

% of whole surface area effected by radiation intensity		(KWh/m2)	View
0.02		5	
0.07		4.5	
0.23	=1.12	4	
0.8		3.5	
4.67		3	Overall
12.04		2.5	
14.1		2	67.87%
18.98		1.5	
21.9		1	
27.18		0.5	

Figure 59 *Evaluation and Results: of Abu-Dhabi Market*

Optimisation Analysis of the Best Solution: Abu-Dhabi Market, Horizontal:

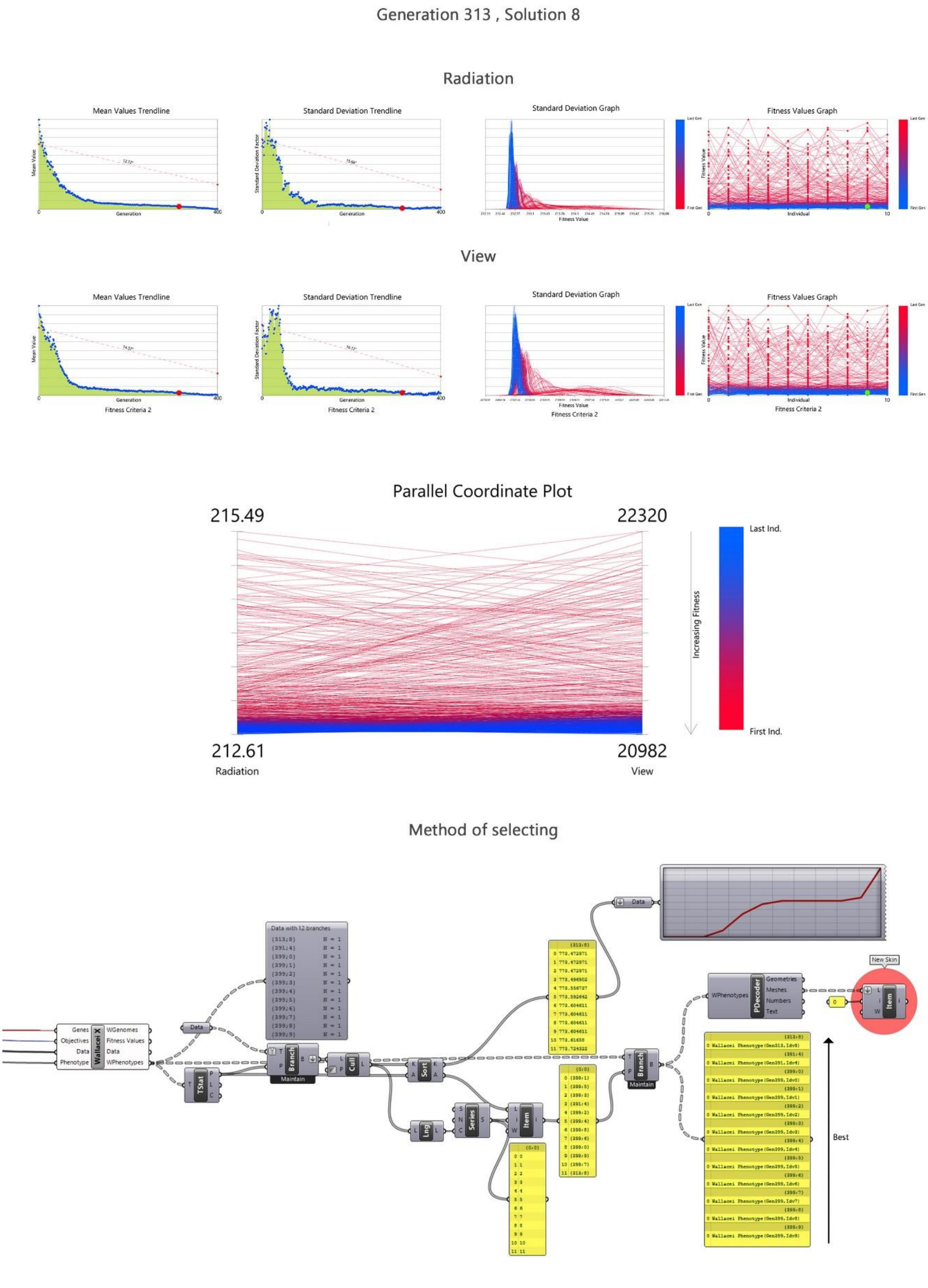


Figure 60 Optimisation Graphs of Generation 313

4.1.4.1 Al-Hilal tower, Vertical:

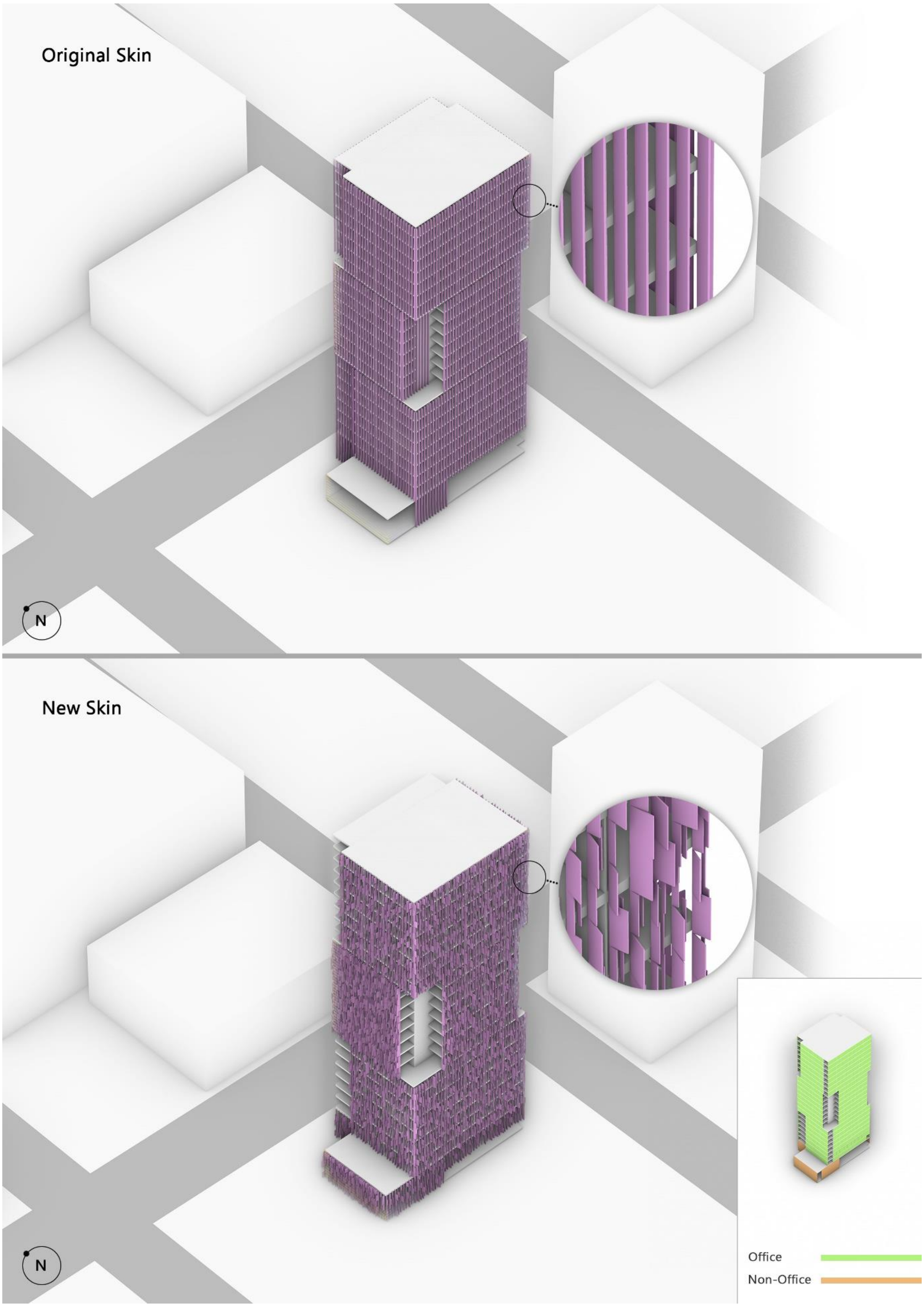


Figure 61 *Al-Hilal tower with vertical shadings*

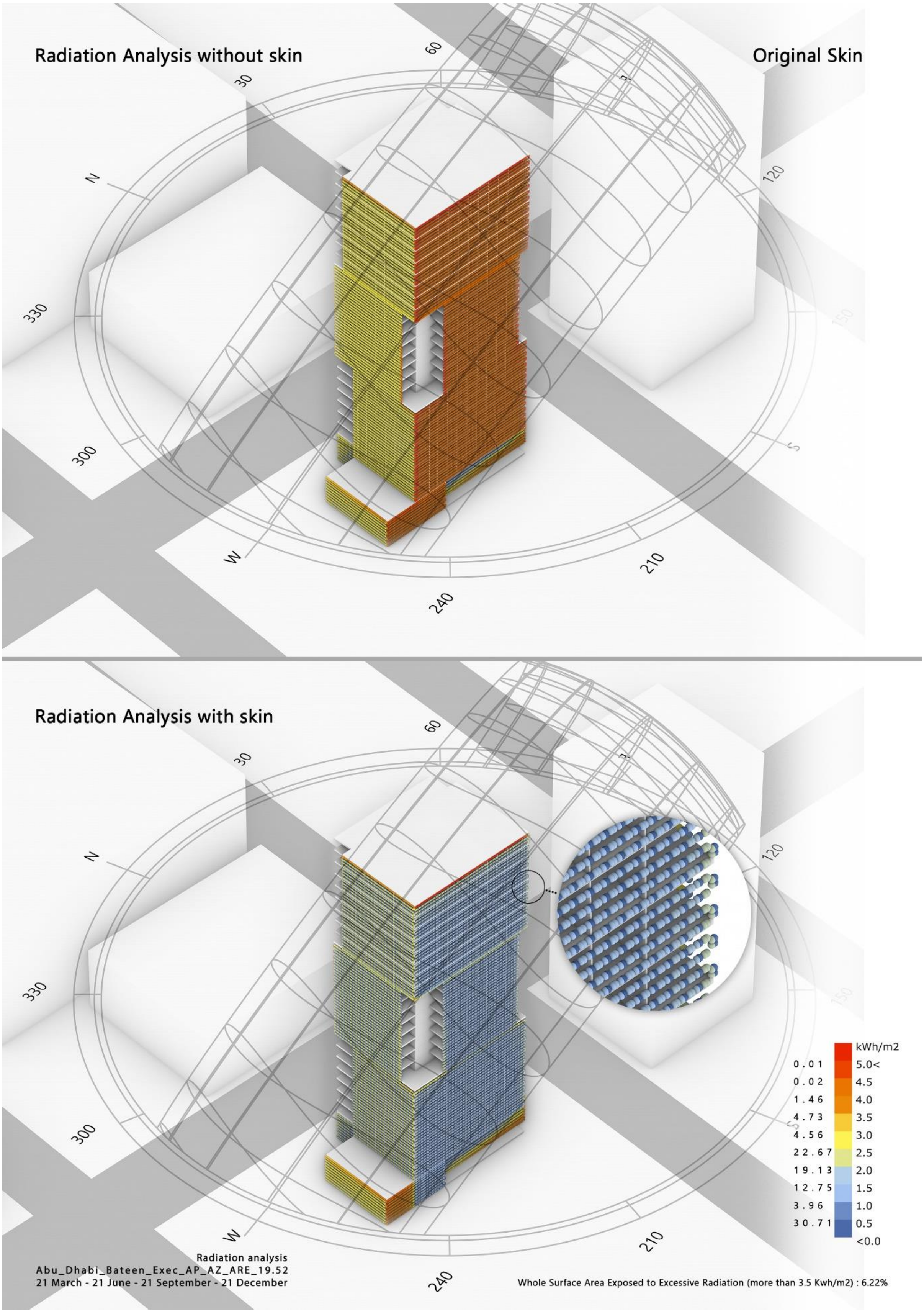


***Figure 62** Radiation Analysis of Al-Hilal tower with the original skin*

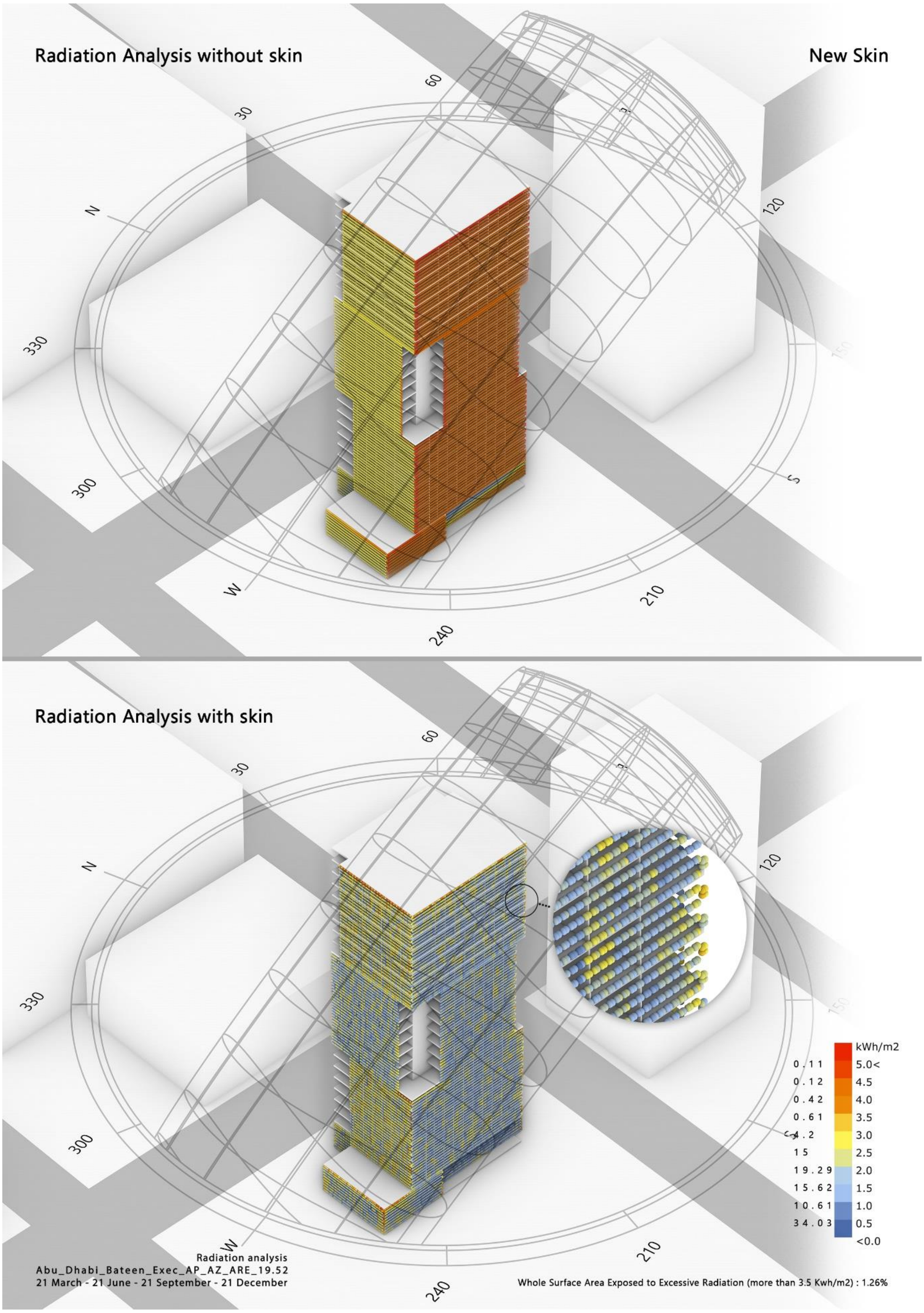


***Figure 63** Radiation Analysis Al-Hilal tower with the evolved skin*

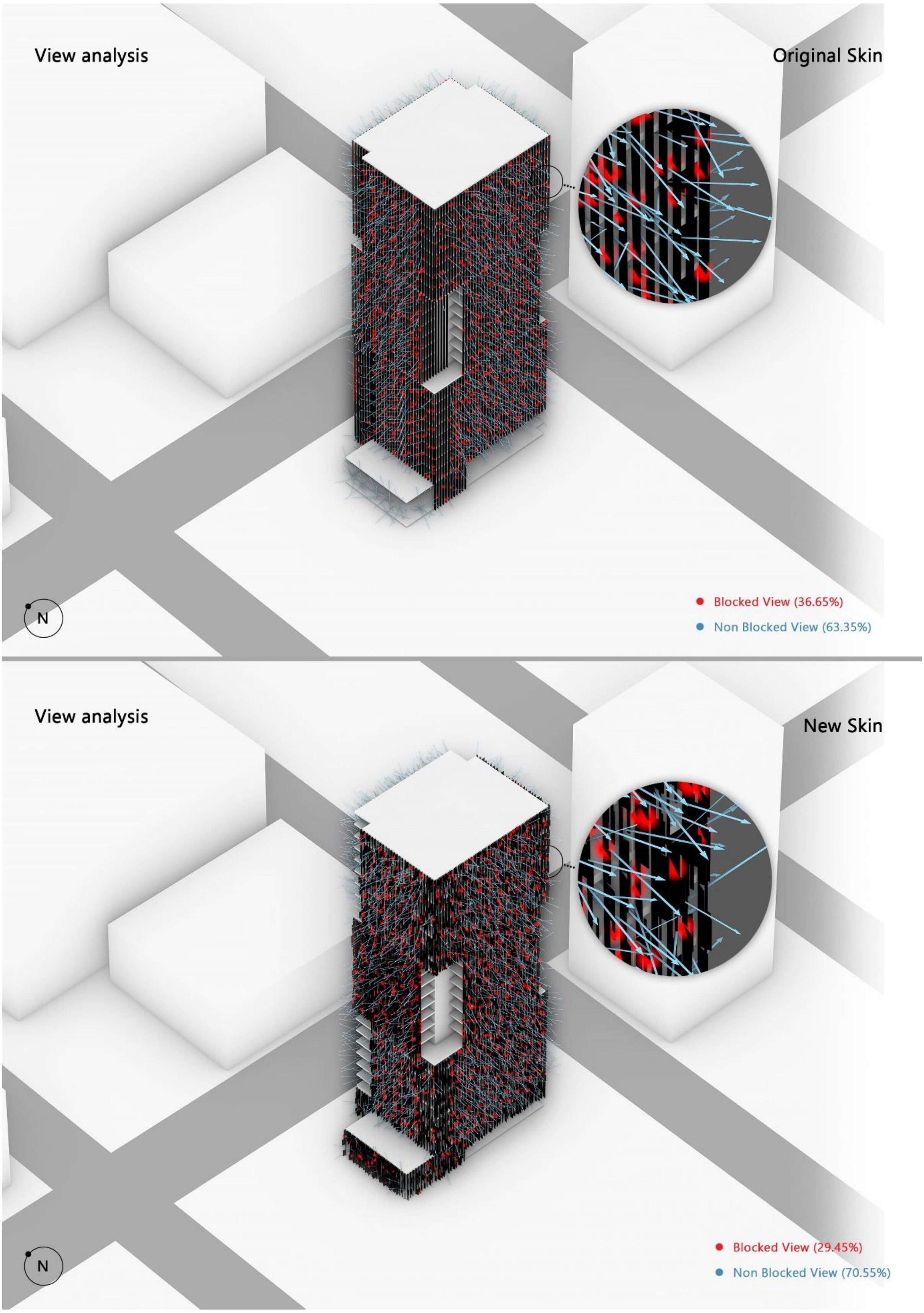


Figure 64 *View Analysis of the Al-Hilal tower*

Evaluation and Results: the Al-Hilal tower

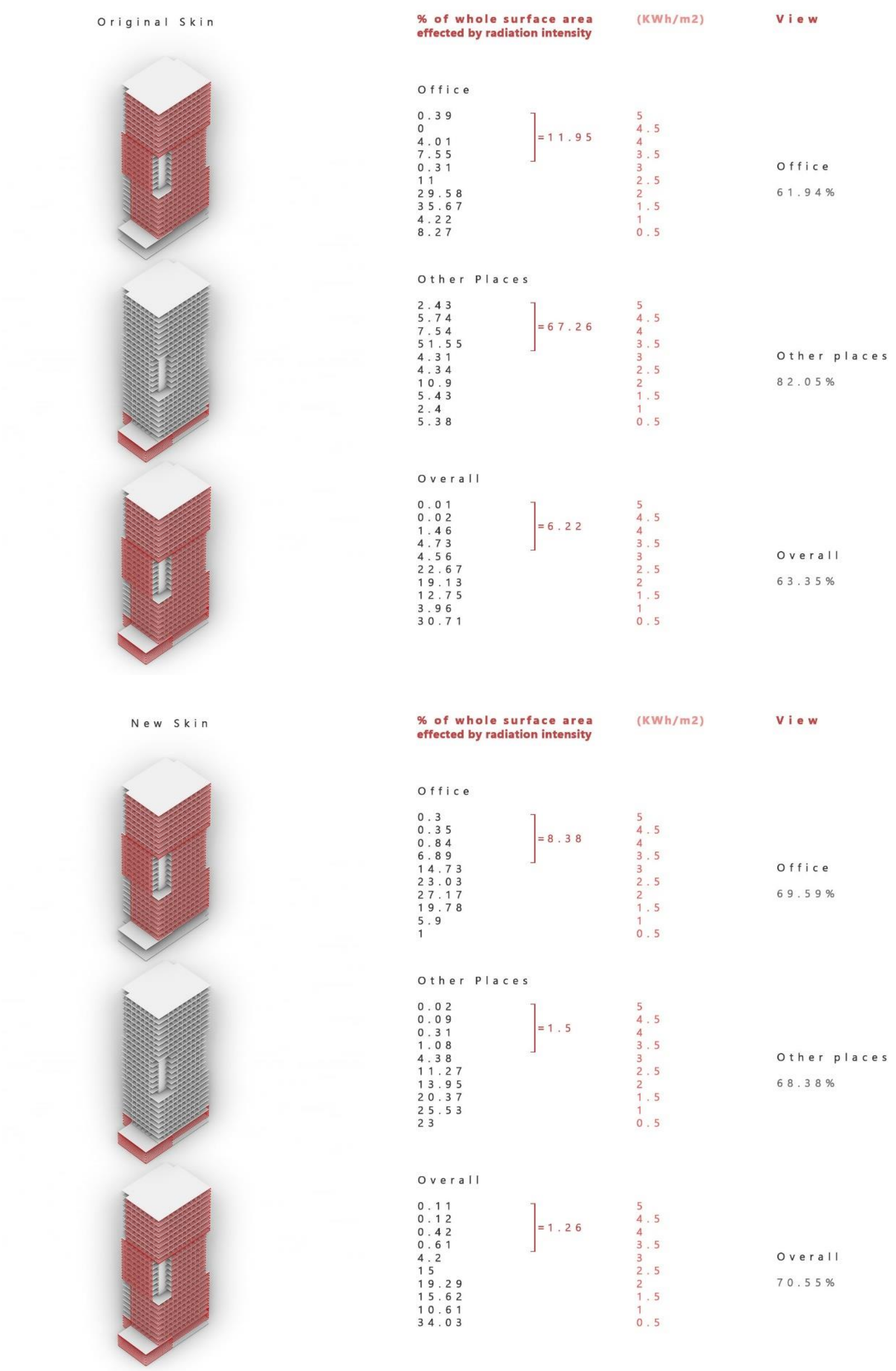


***Figure 65** Evaluation and Results: the Al-Hilal tower*

Optimisation Analysis of the Best Solution: Al-Hilal tower, Vertical

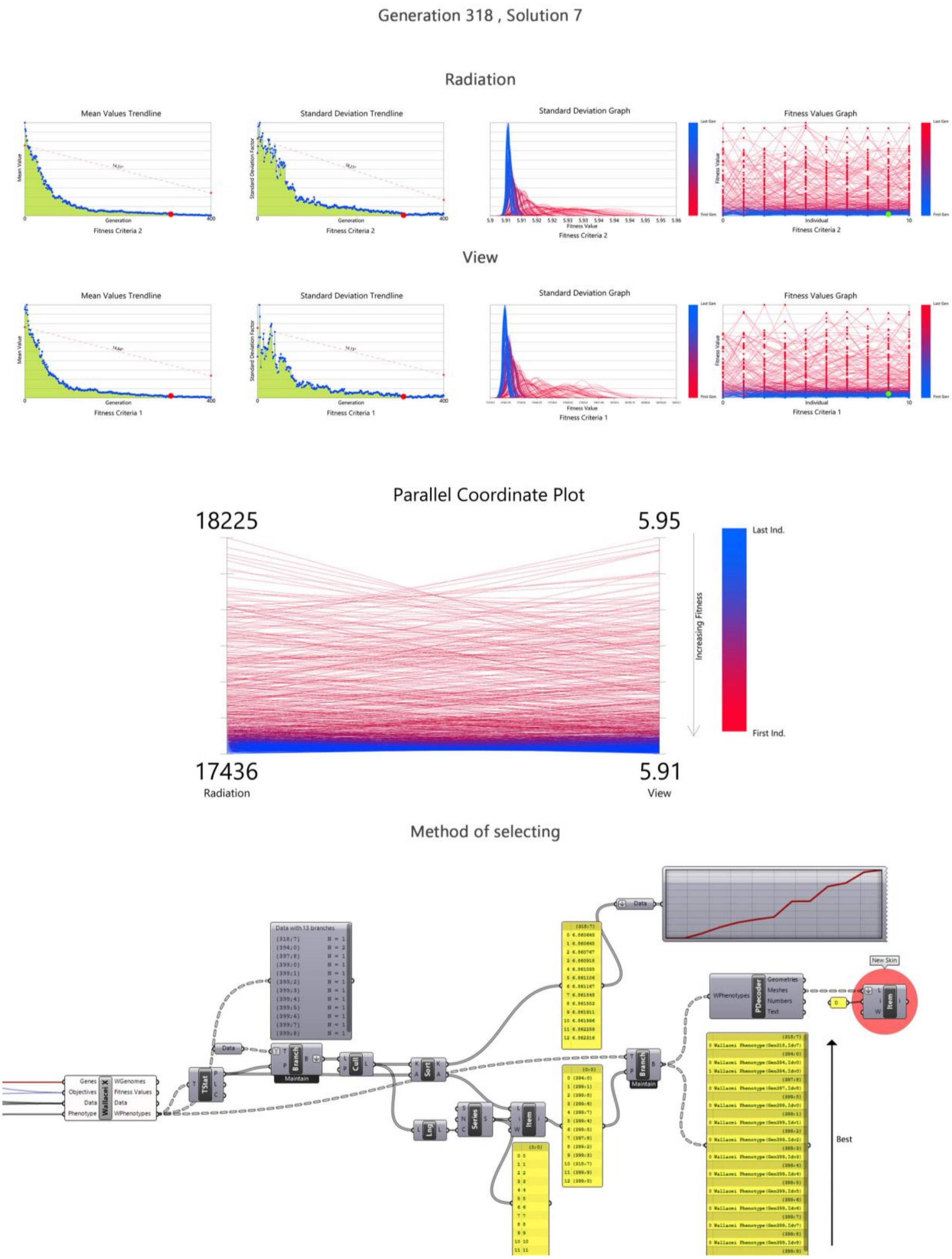


Figure 66 *Optimisation Graphs of Generation 318*

4.1.4.2 PIF Tower, with Square (Crossed) Shadings:

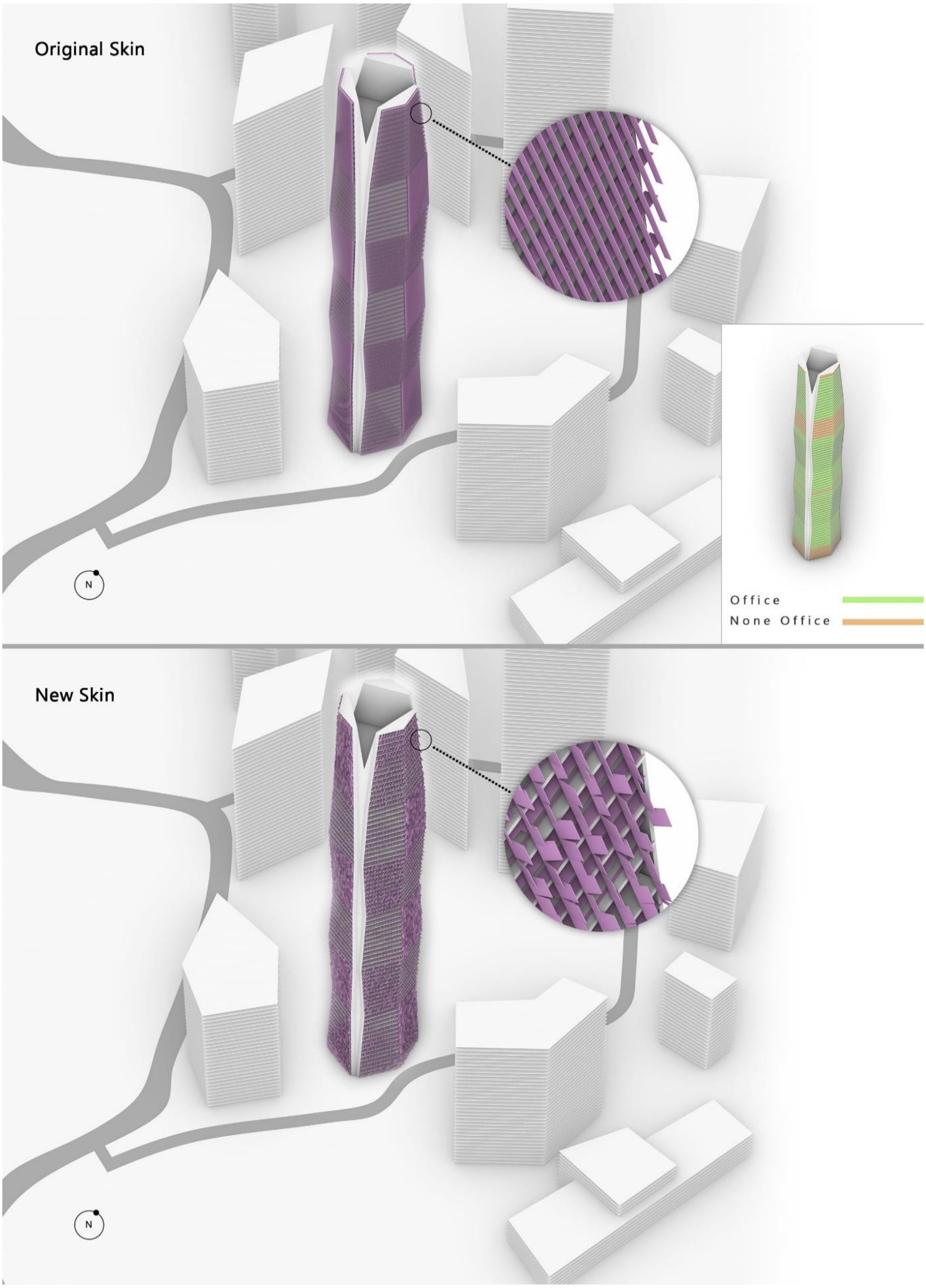


Figure 67 *PIF Tower, with Square (Crossed) Shadings*

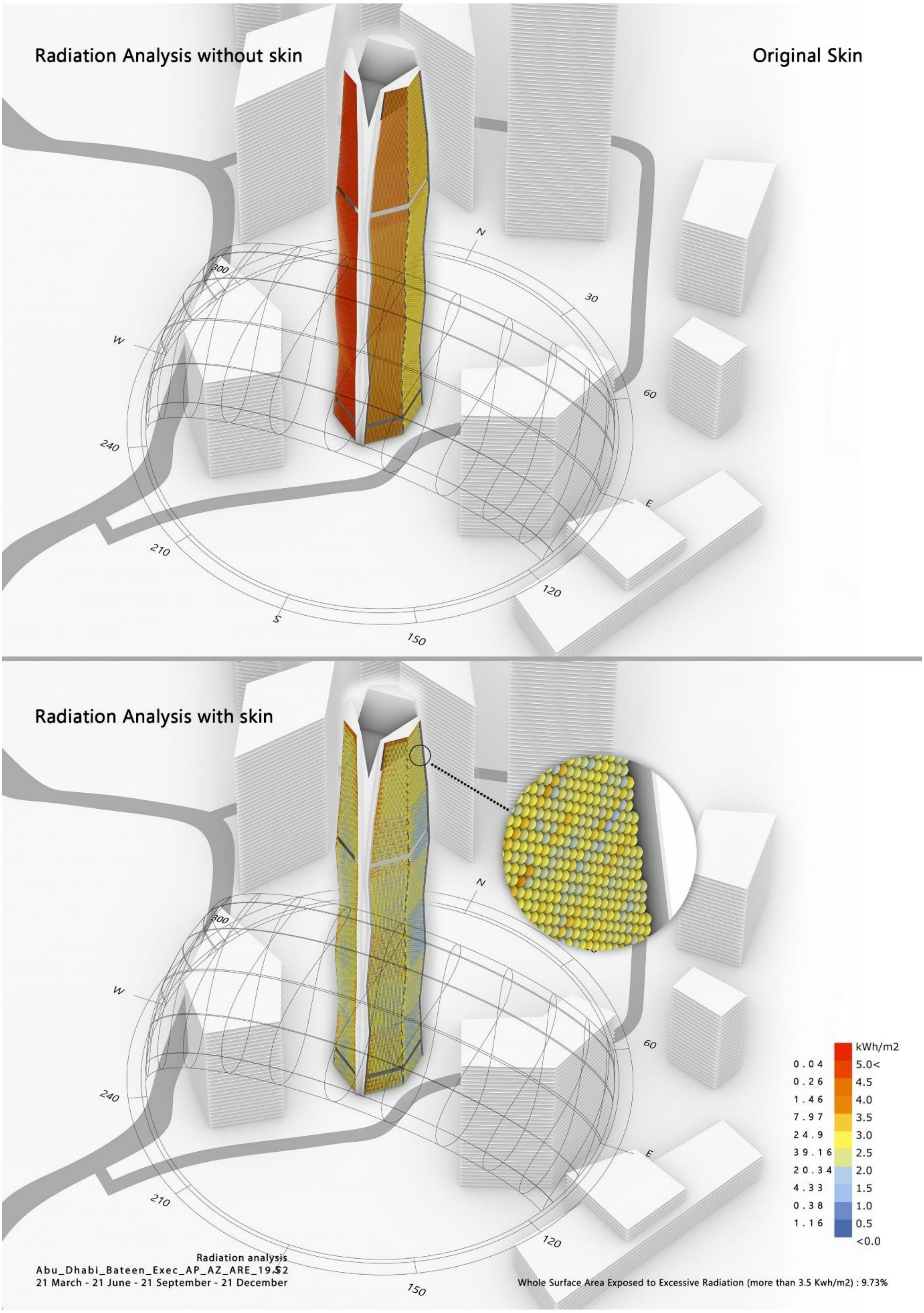


***Figure 68** Radiation Analysis of the PIF Tower with the original skin*

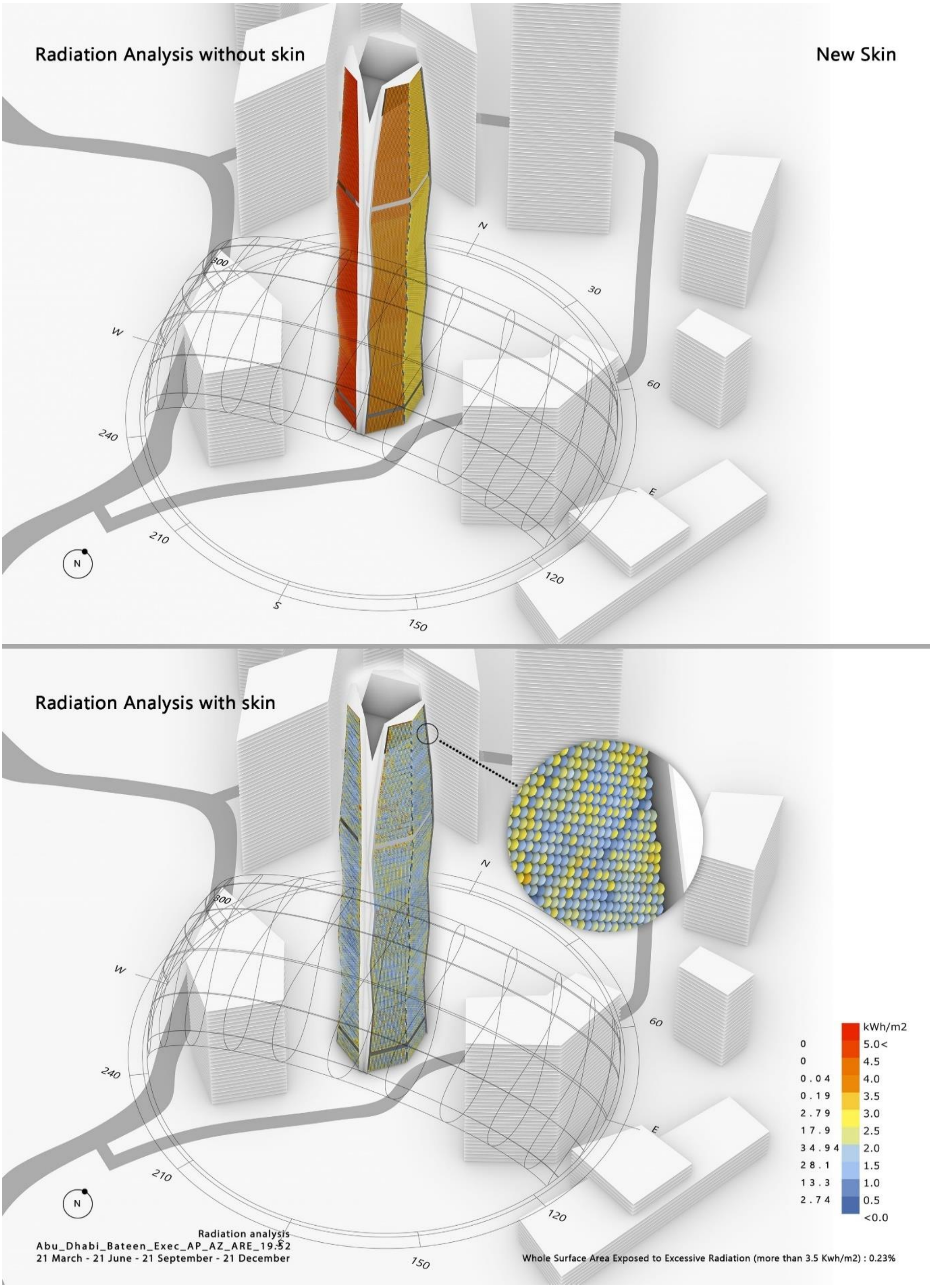


Figure 69 *Radiation Analysis of the PIF Tower with the evolved skin*

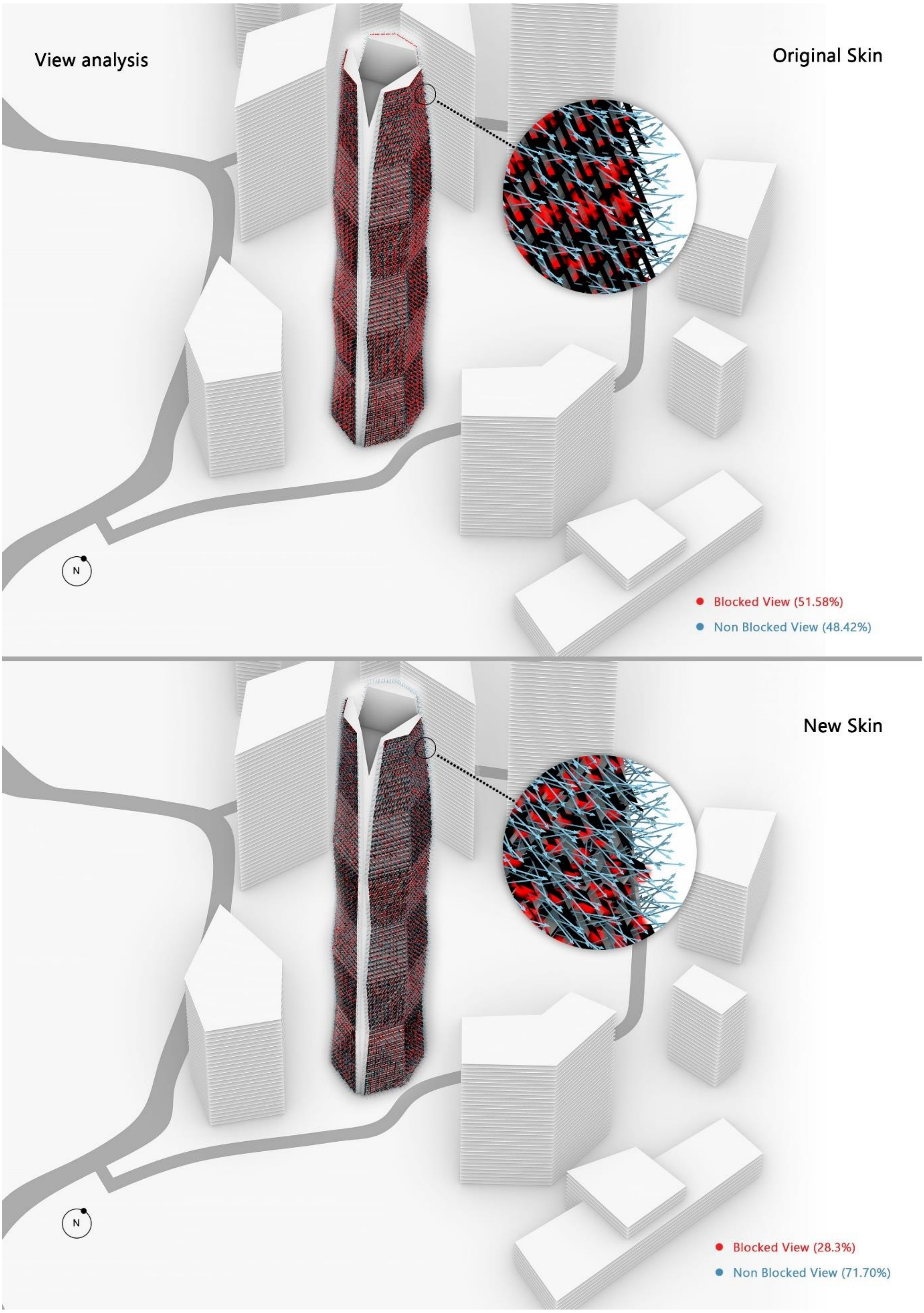


Figure 70 *View Analysis of the PIF Tower*

Evaluation and Results: *the* PIF Tower

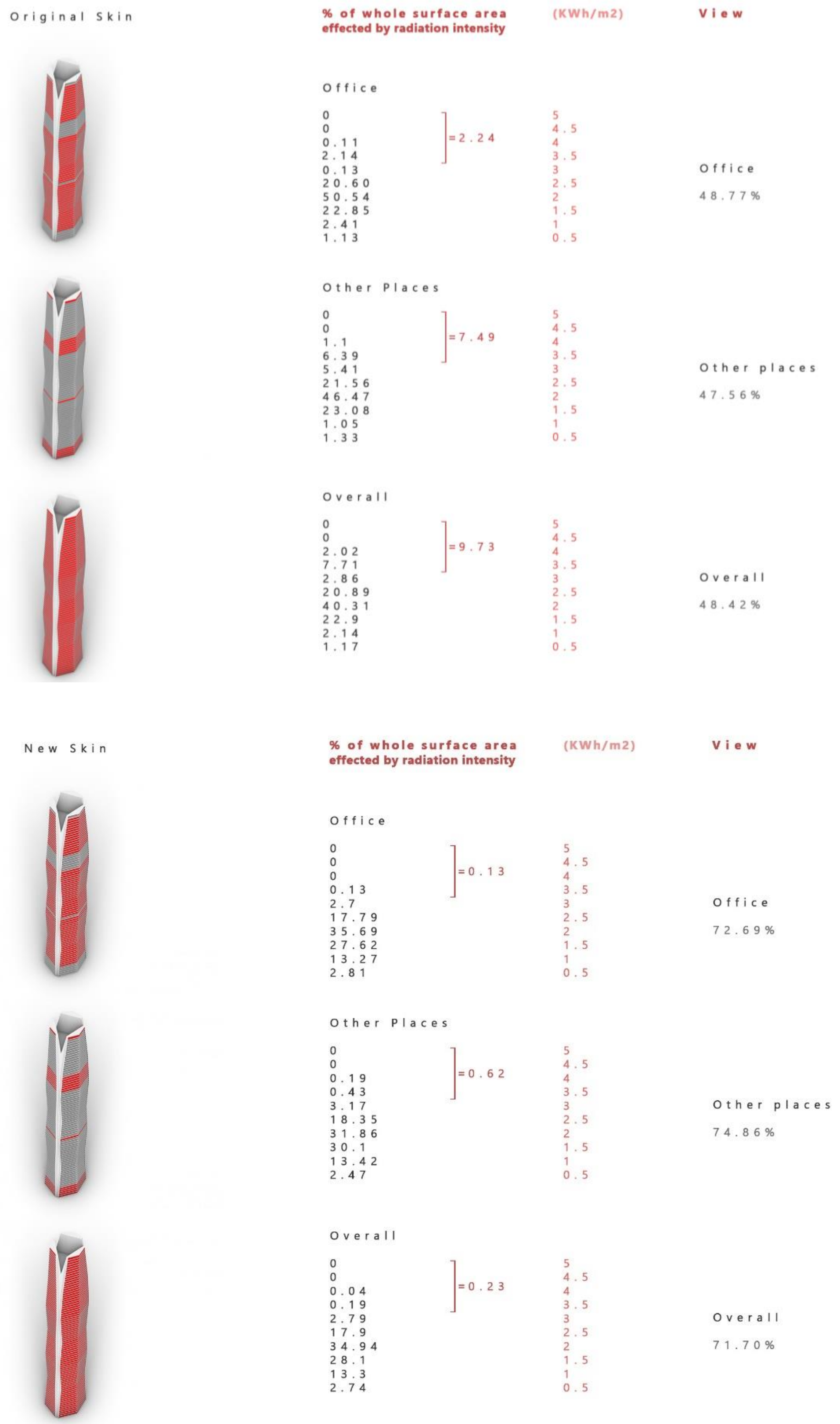


Figure 71 *Evaluation and Results: the PIF Tower*

Optimisation Analysis of the Best Solution, the PIF Tower

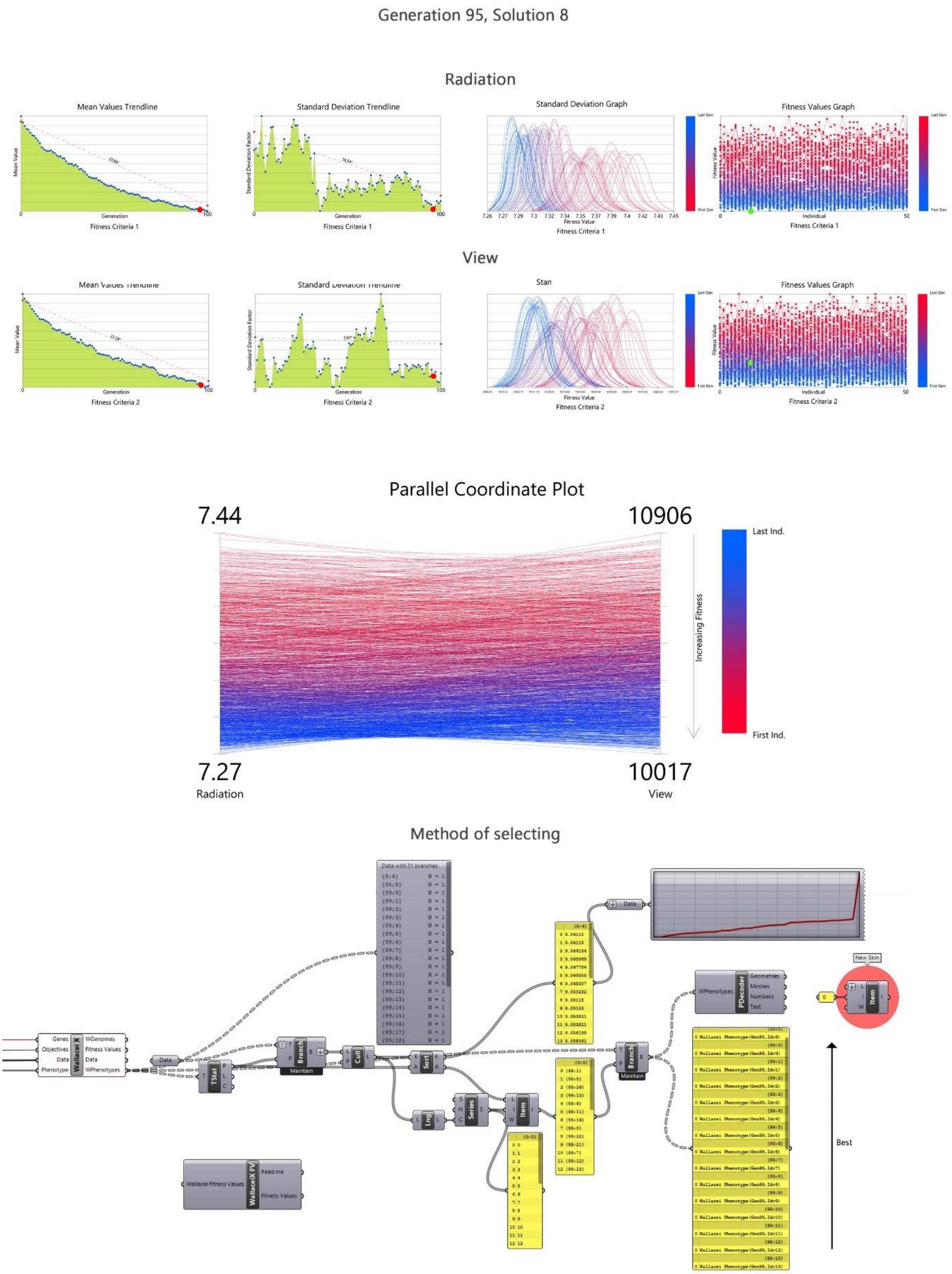


__Figure 72__ Optimisation Graphs of the Best Solution, the PIF Tower, Generation 95

4.1.4.3 Al-Bahr Towers and Cellular Pattern:

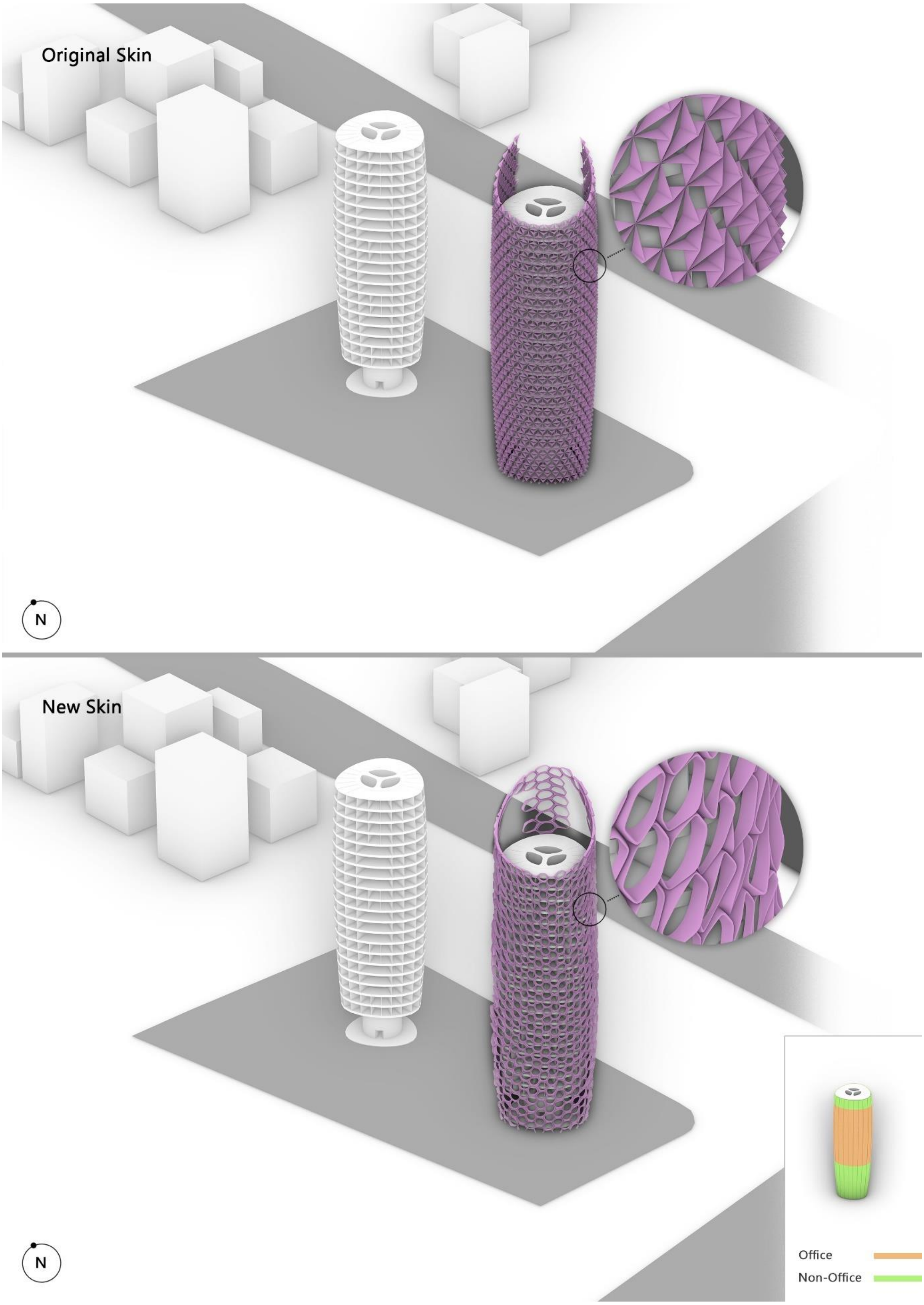


Figure 73 *The Al-Bahr towers and Cellular Pattern (before and after)*

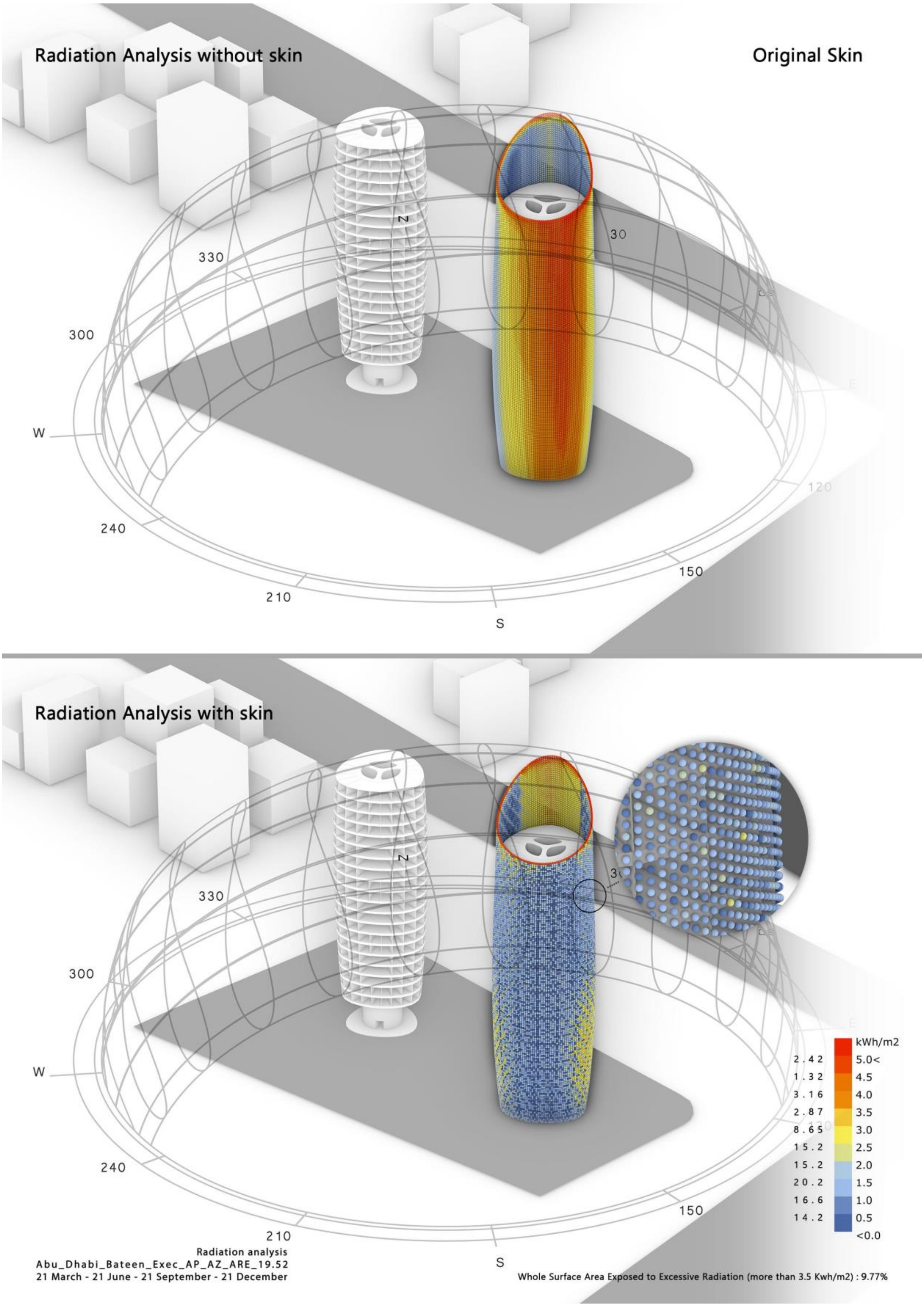


Figure 74 *Radiation Analysis of the Al-Bahr towers with the original skin*

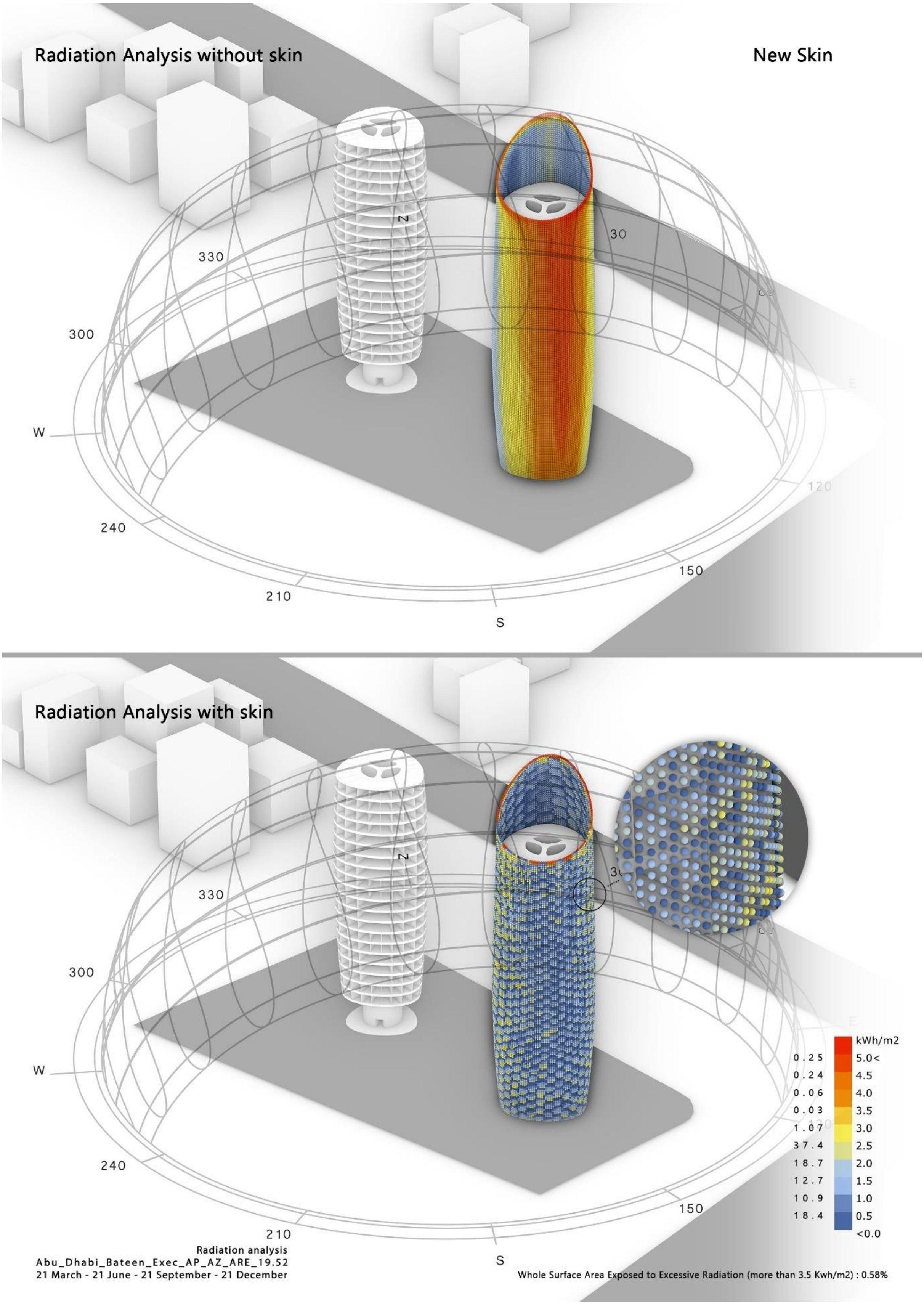


Figure 75 *Radiation Analysis of the Al-Bahr towers with the evolved skin*

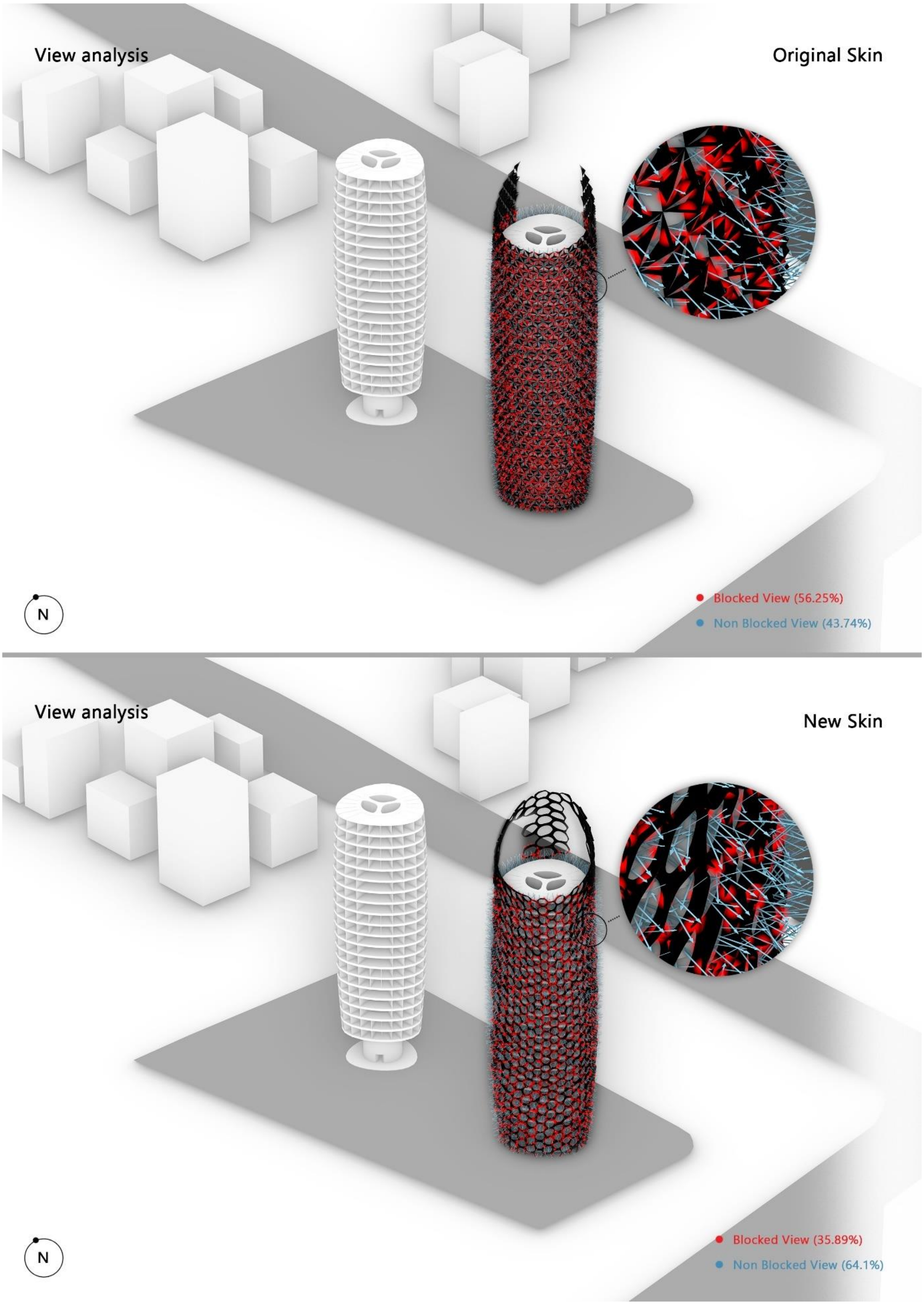


***Figure 76** View Analysis of the Al-Bahr towers*

Evaluation and Results: the Al-Bahr towers

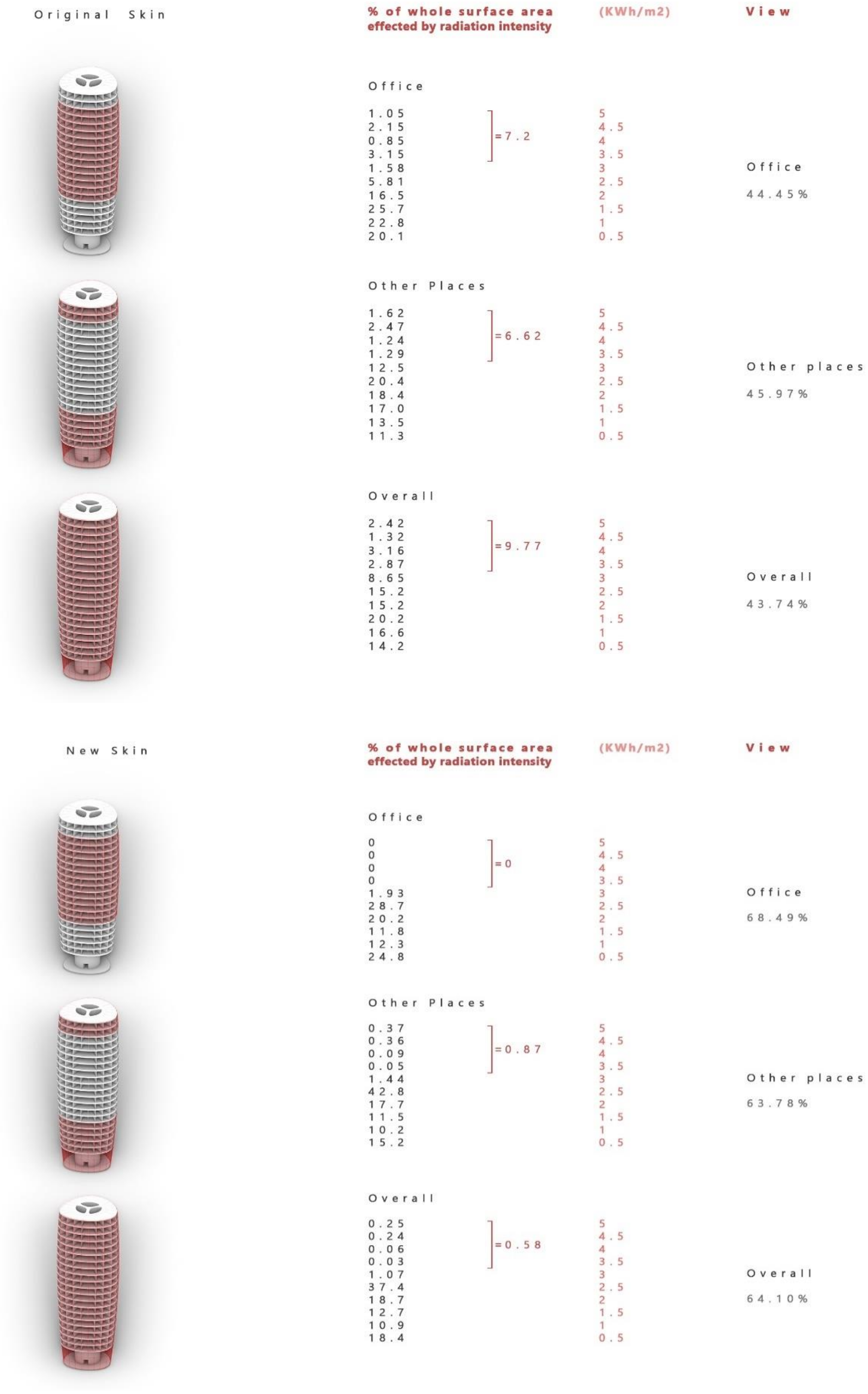


Figure 77 *Evaluation and Results: the Al-Bahr towers*

Optimisation Analysis of the Best Solution, the Al-Bahr towers

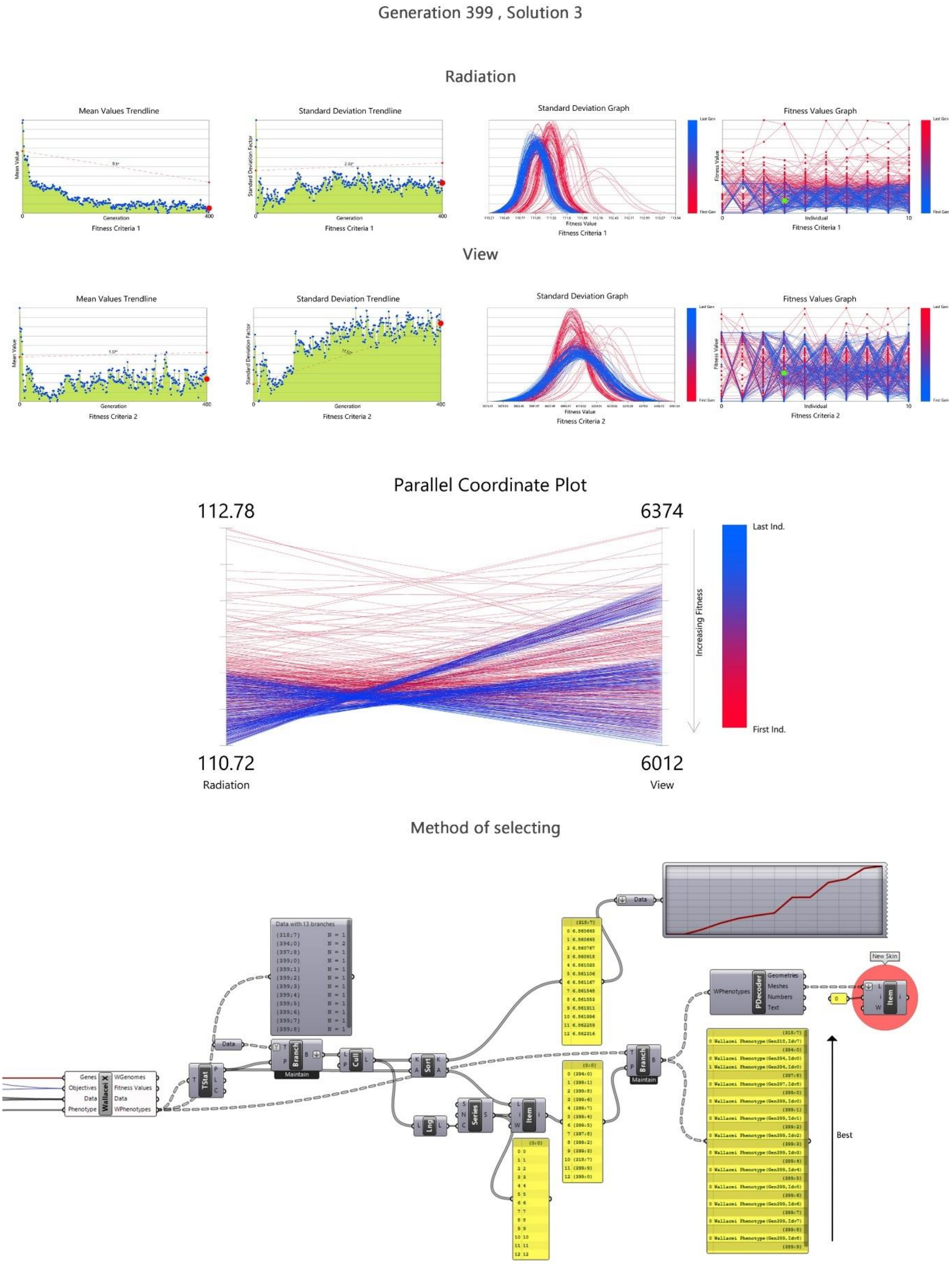


Figure 78 Optimisation Graphs of the Best Solution, the Al-Bahr towers, Generation 399

4.1.4.4 Al-Bahr Towers, Horizontal Shadings:

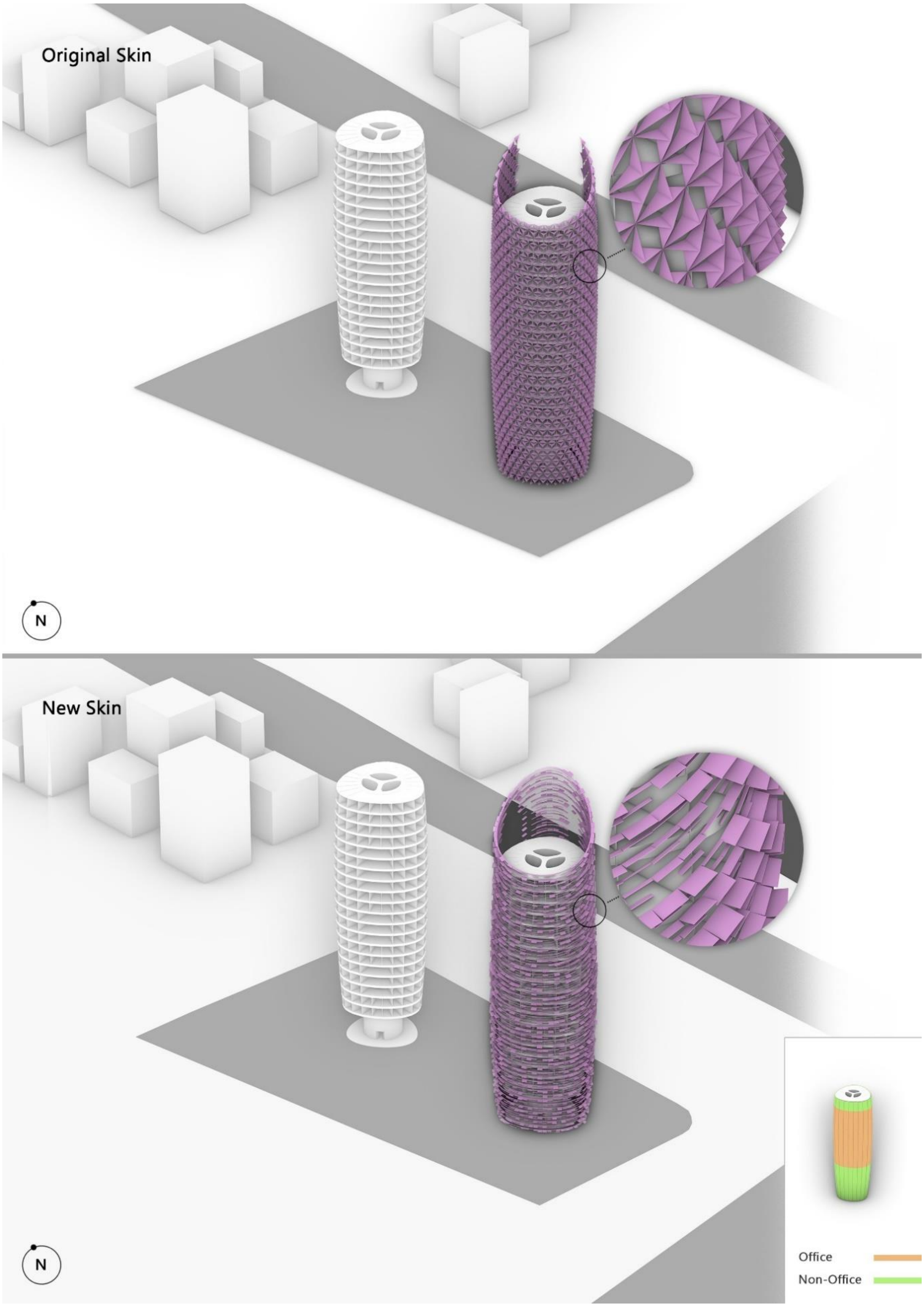


Figure 79 *Al-Bahr Towers, Horizontal Shadings (Before and After)*

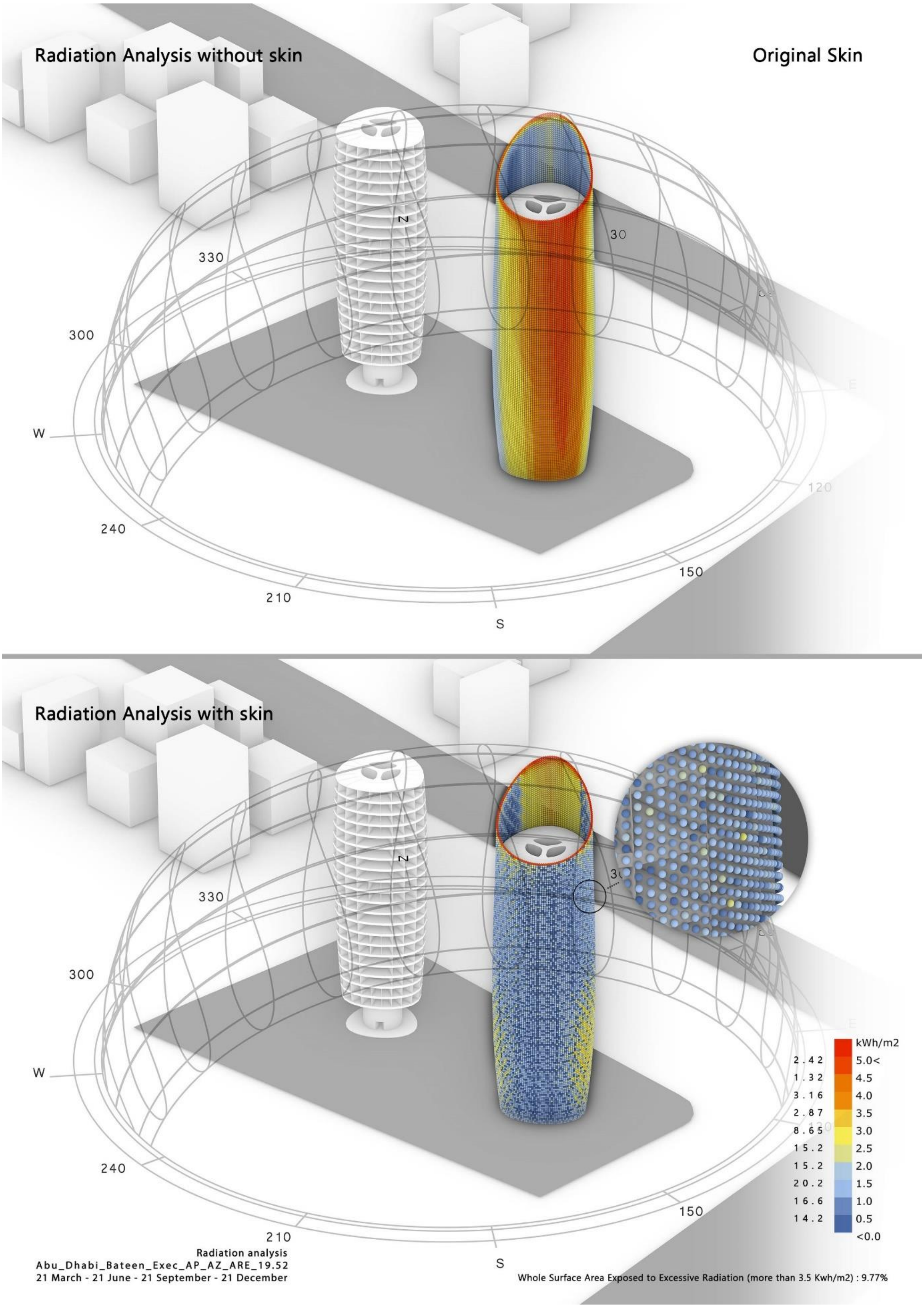


Figure 80 *Radiation Analysis of the Al-Bahr towers with the original skin*

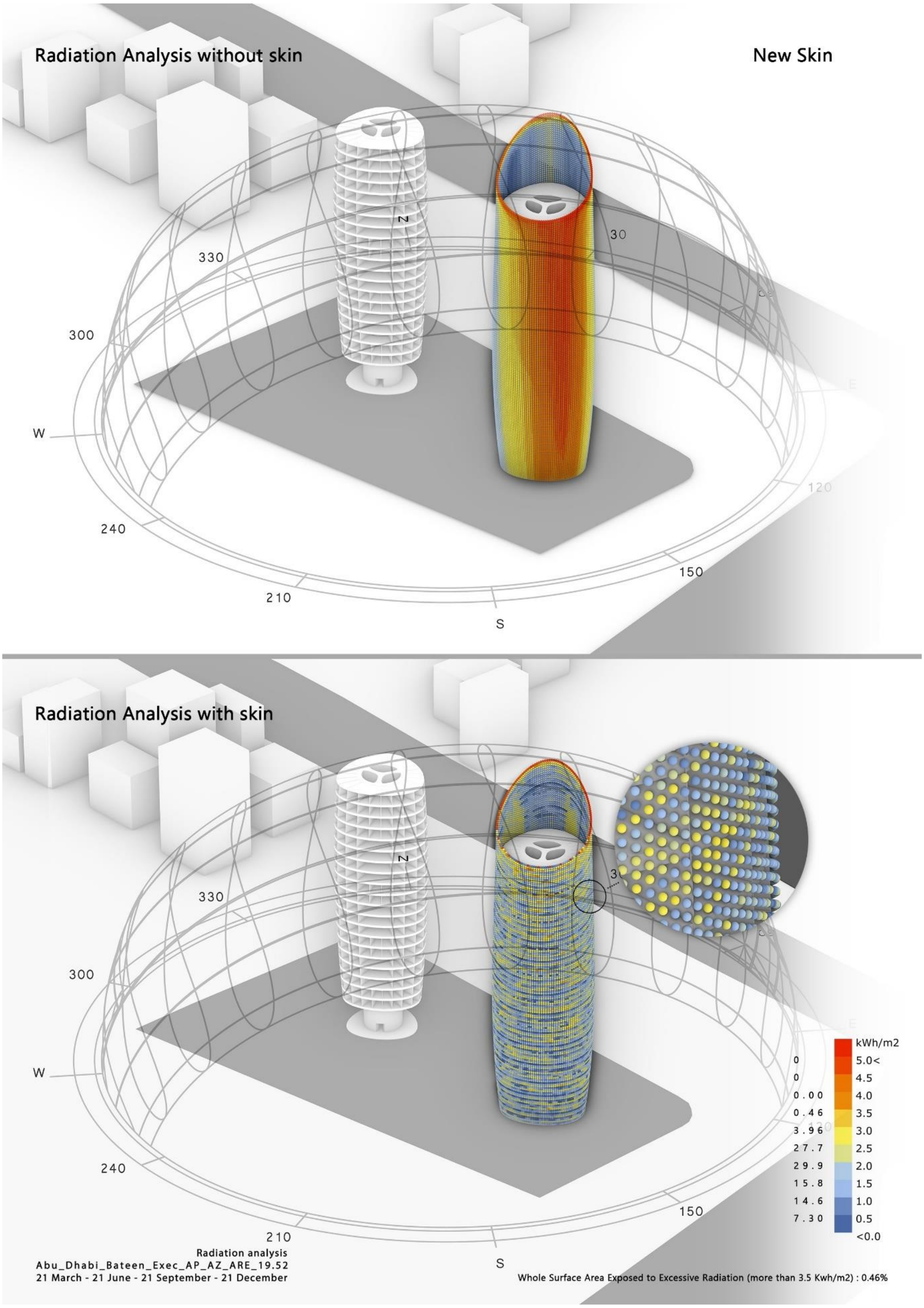


Figure 81 *Radiation Analysis of the Al-Bahr Towers with the Evolved Horizontal Shadings*

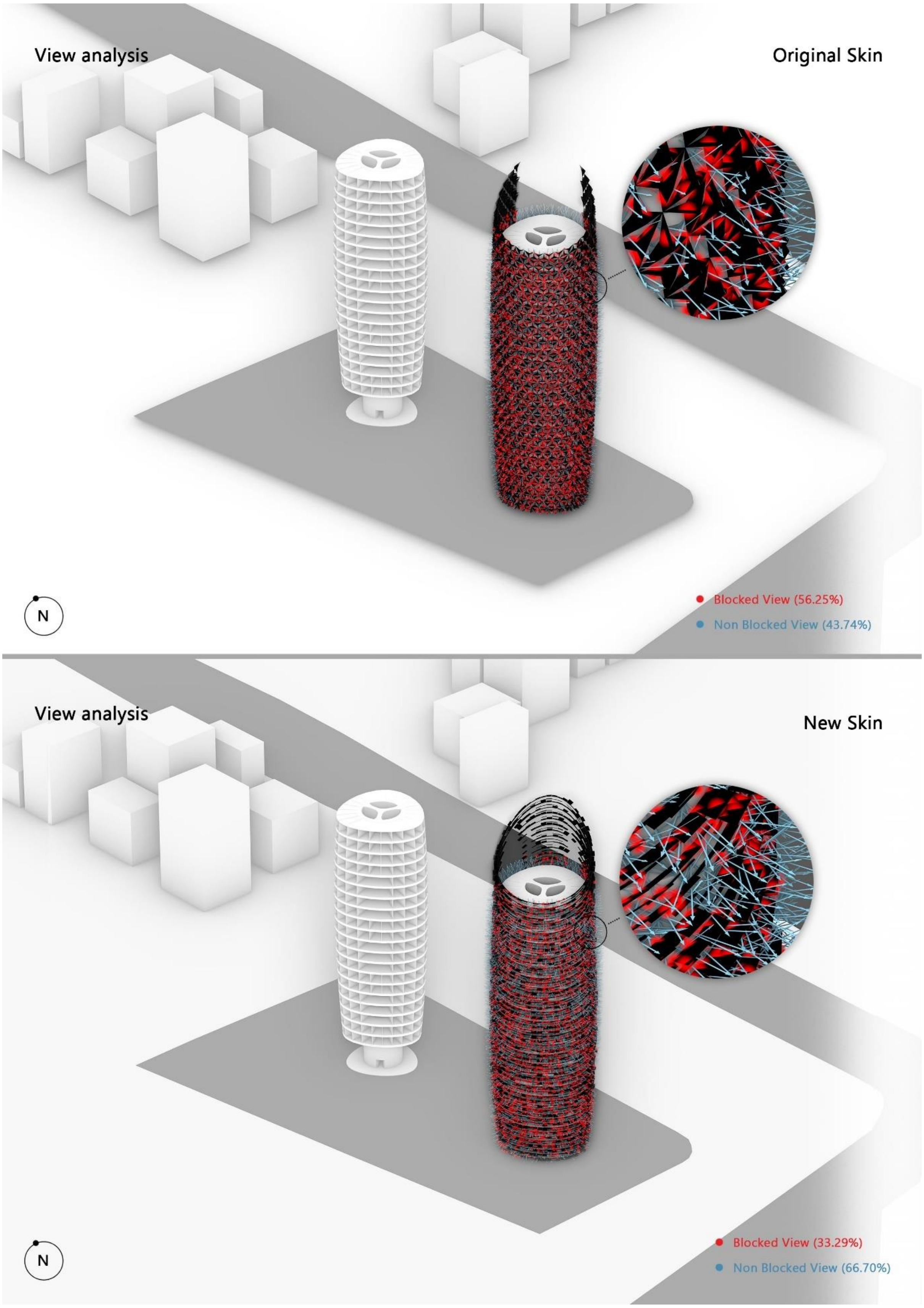


Figure 82 *View Analysis of the Al-Bahr Towers, Horizontal Shadings*

Evaluation and Results: Al-Bahr Towers, Horizontal Shadings:

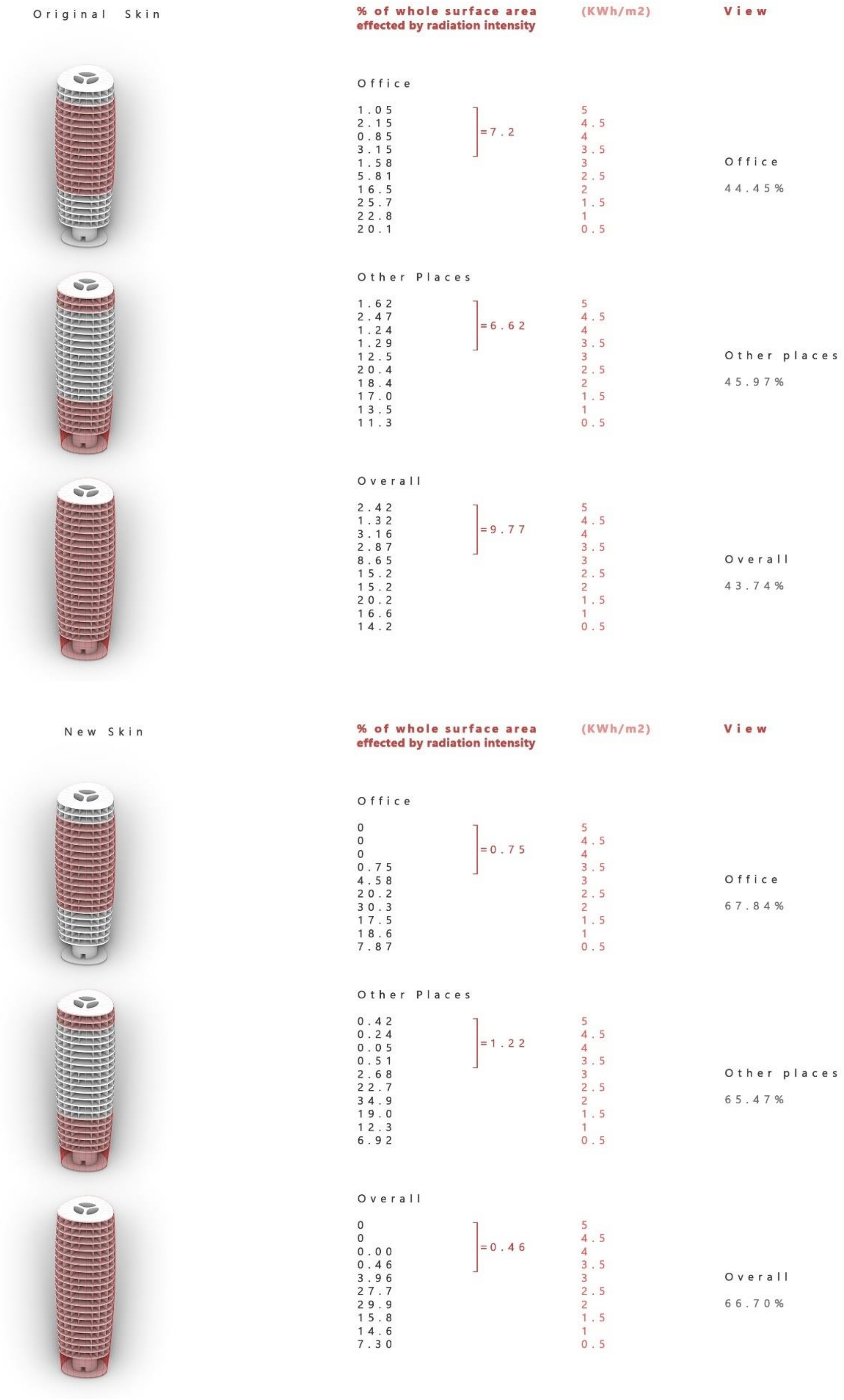


Figure 83 *Evaluation and Results: Al-Bahr Towers, Horizontal Shadings*

Optimisation Analysis of the Best Solution, Al-Bahr Towers, Horizontal Shadings

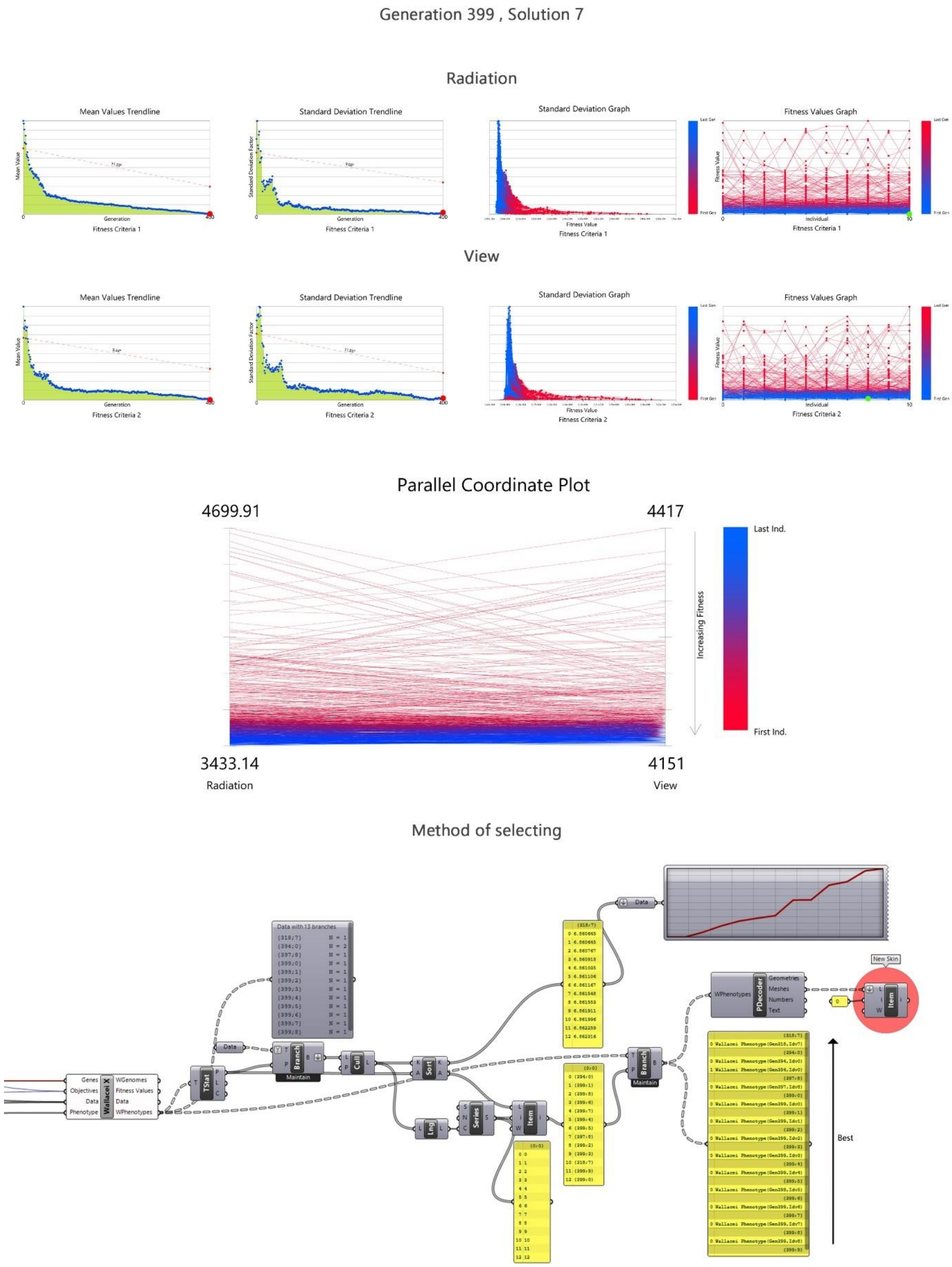


***Figure 84** Optimisation Graphs of the Best Solution, Al-Bahr Towers, Horizontal Shadings, Generation 399*

4.1.4.5 Al-Bahr Towers, Vertical Shading

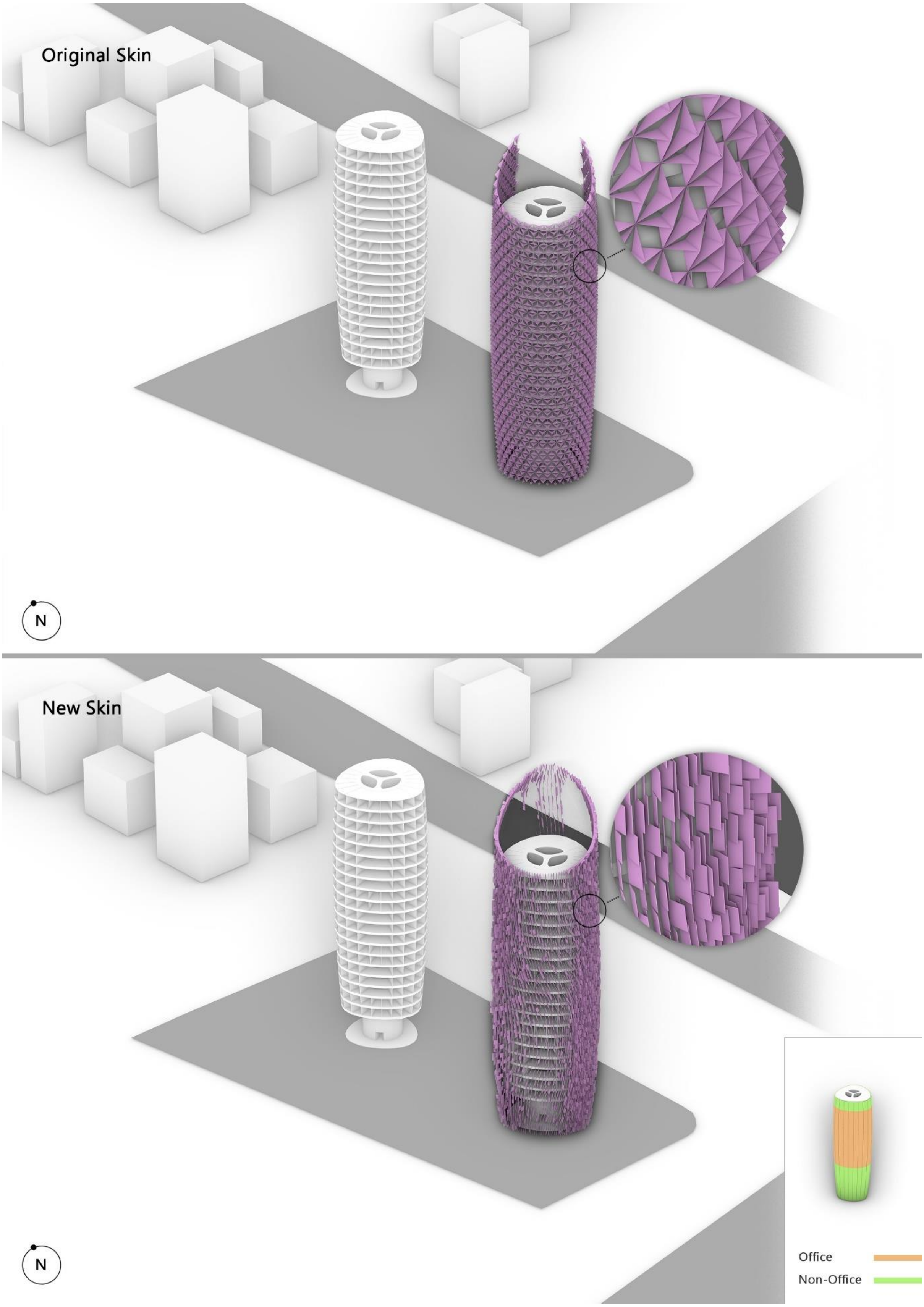


Figure 85 *Al-Bahr Towers, Vertical Shading (Before and After)*

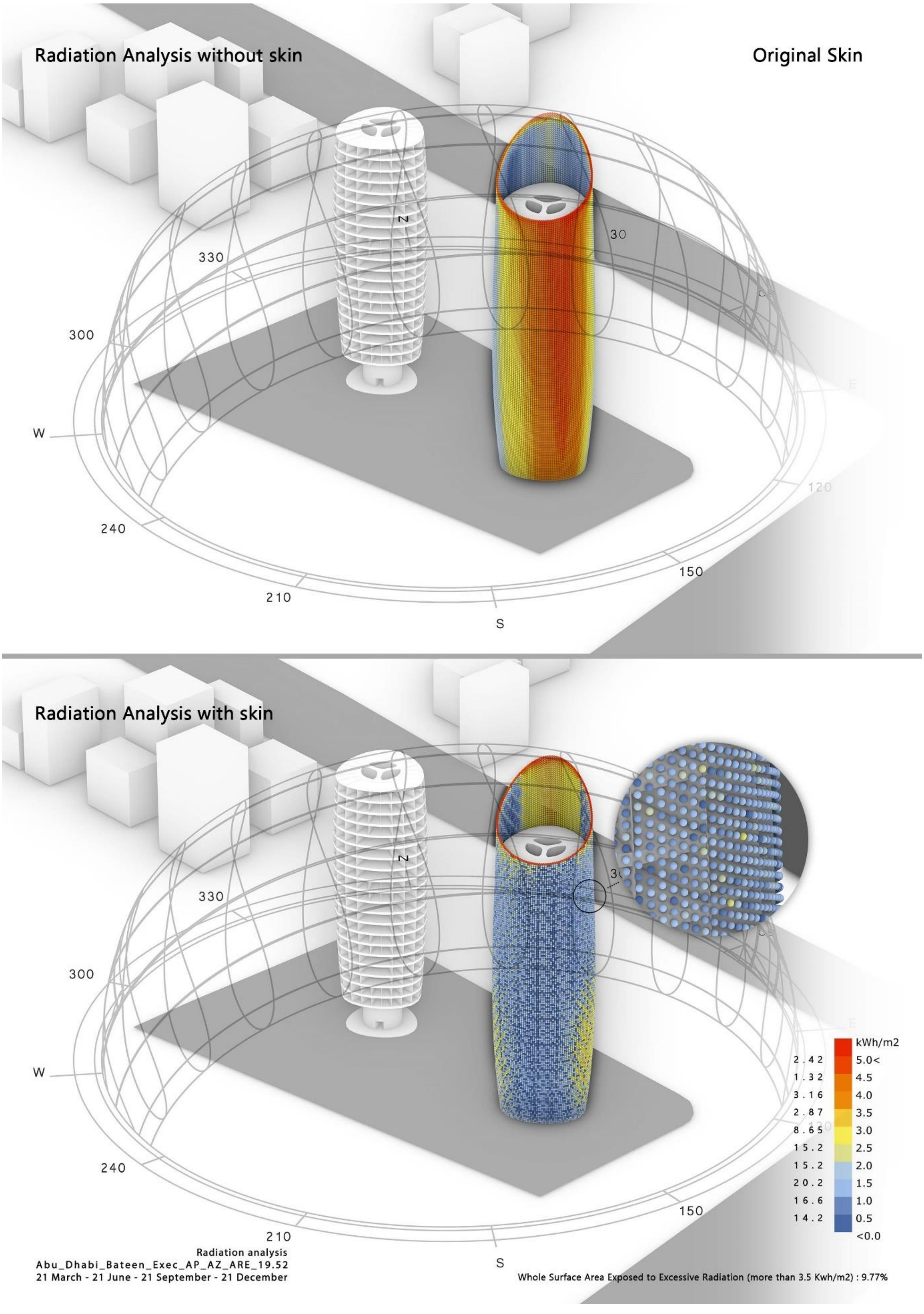


***Figure 86** Radiation analysis of Al-Bahr Towers (Vertical Shading) with the original skin*

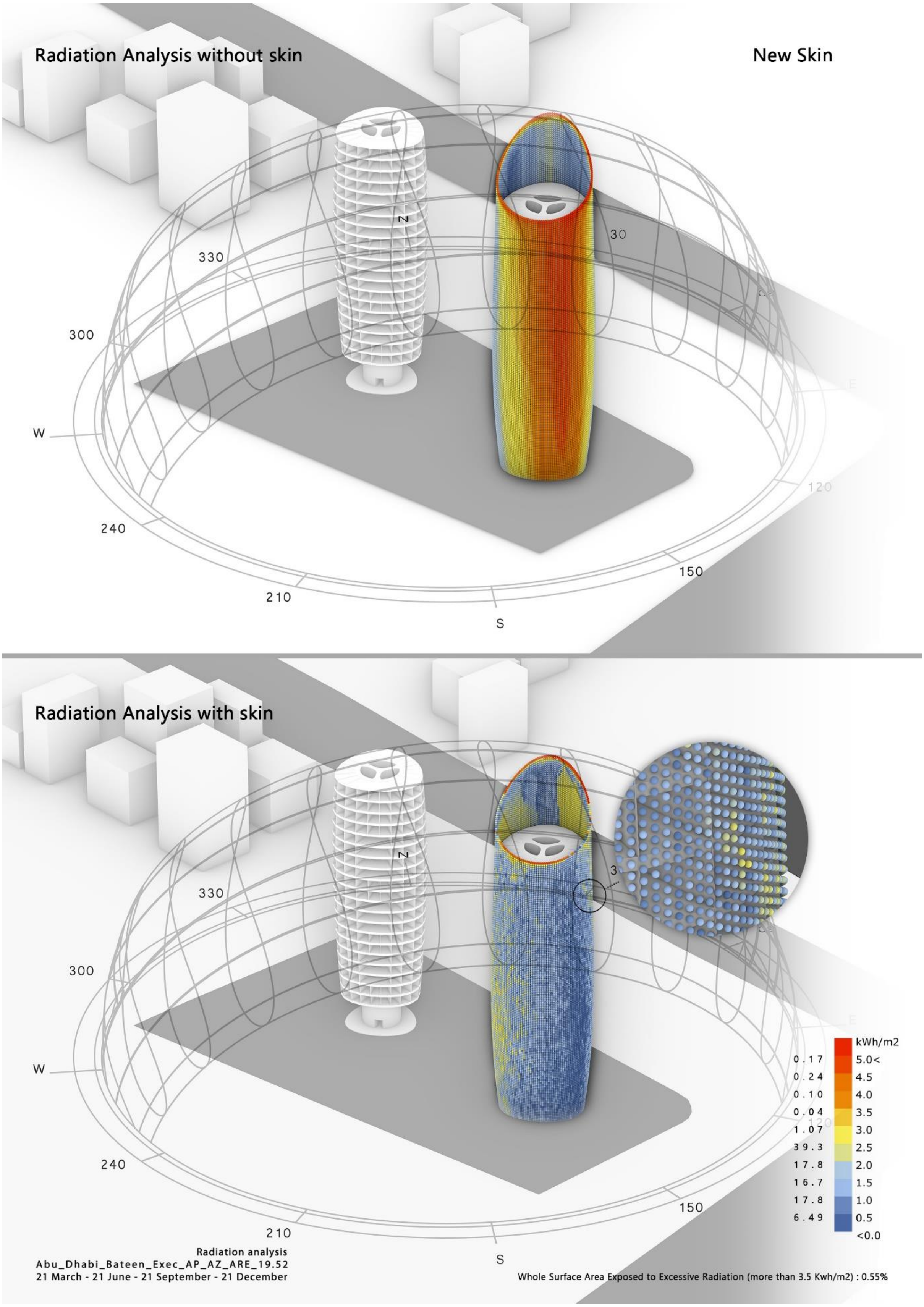


Figure 87 *Radiation analysis of Al-Bahr Towers (Vertical Shading) with the evolved skin*

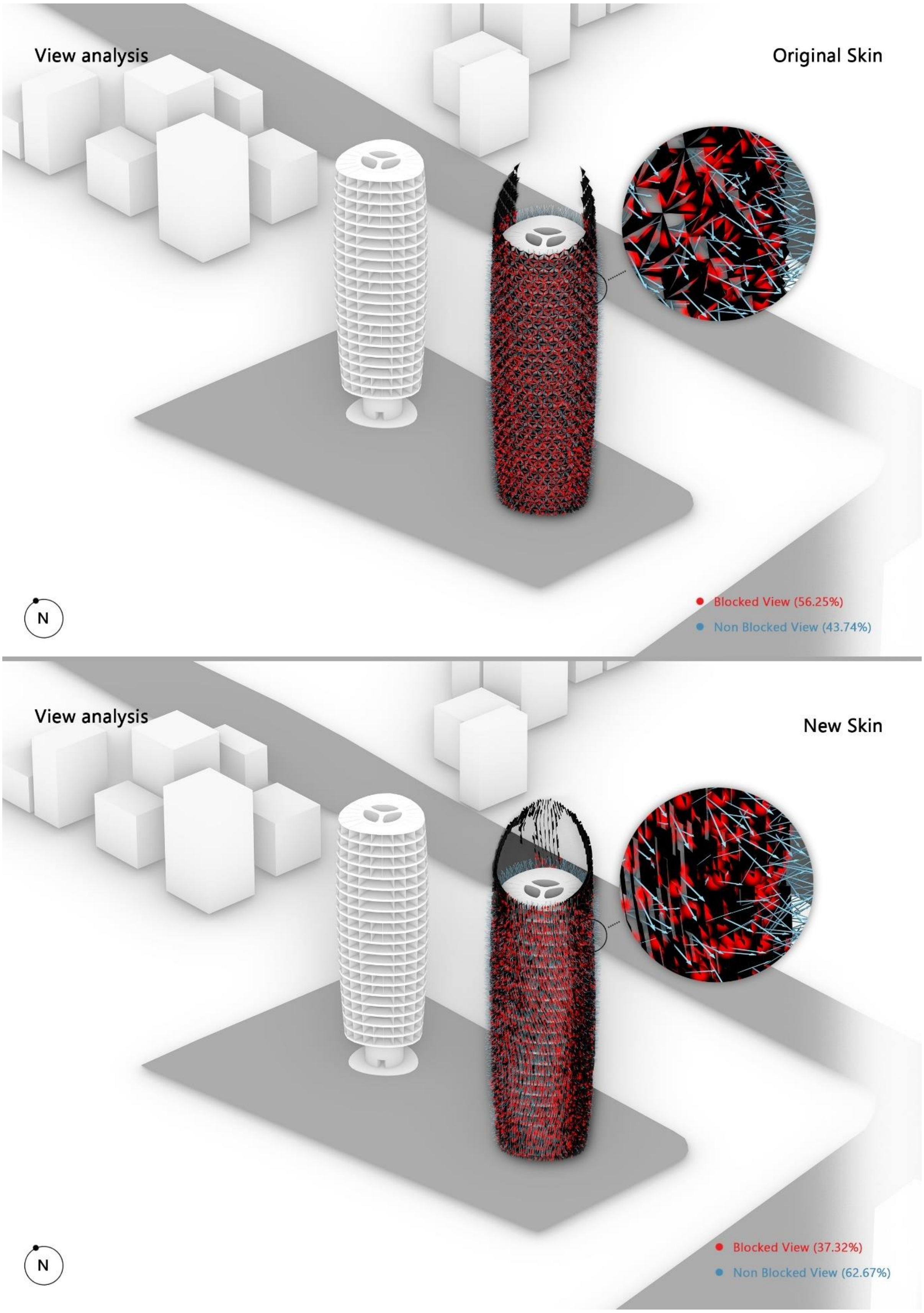


Figure 88 *View Analysis Al-Bahr Towers, Vertical Shading*

Evaluation and Results: the Al-Bahr Towers, Vertical Shading

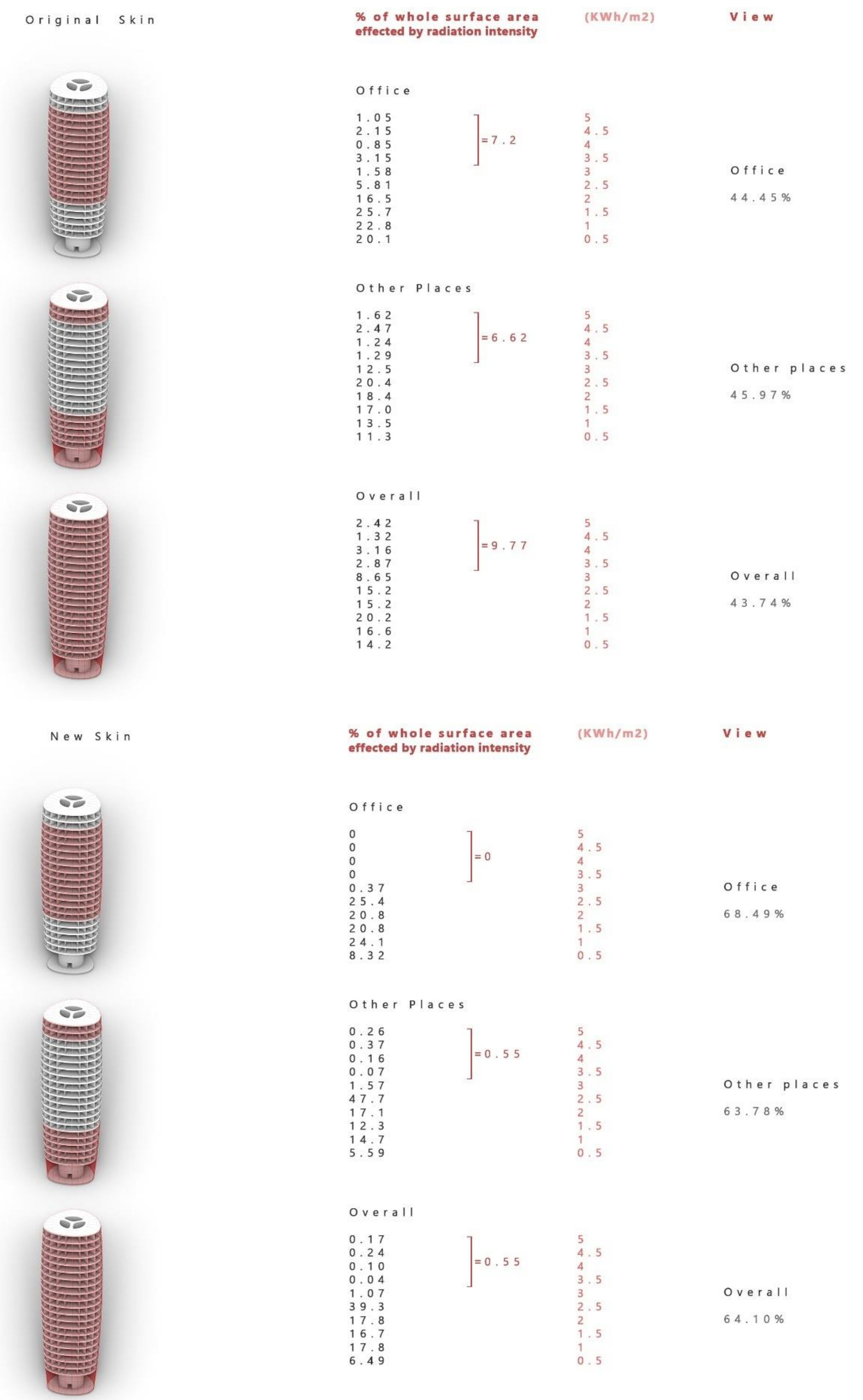


Figure 89 *Evaluation and Results: the Al-Bahr Towers, Vertical Shading*

Optimisation Analysis of the Best Solution of the Al-Bahr Towers, Vertical Shading

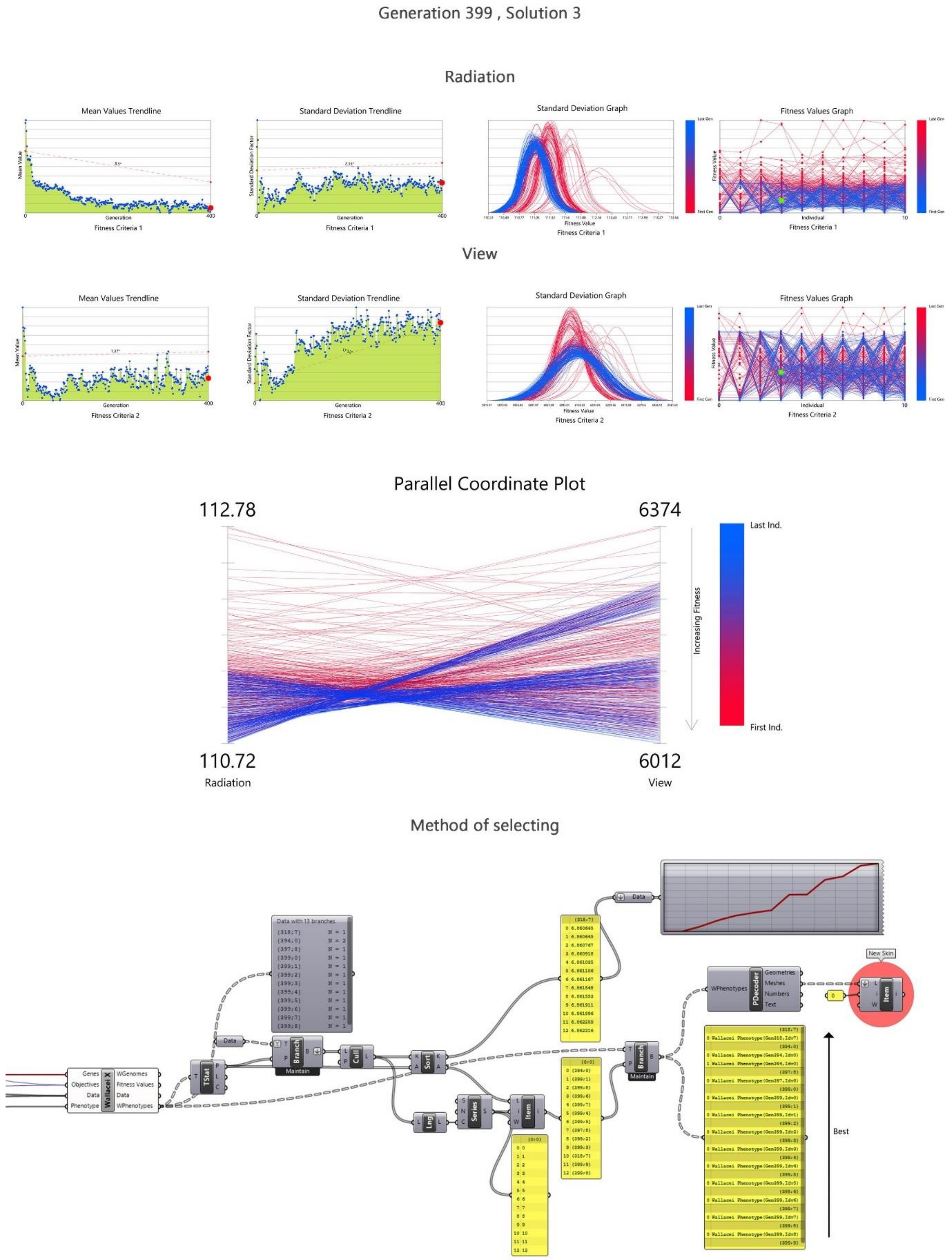


***Figure 90** Optimisation Graphs of the Best Solution of the Al-Bahr Towers, Vertical Shading, Generation 399*

4.1.4.6 Al-Bahr towers, egg-crate (crossed) Pattern:

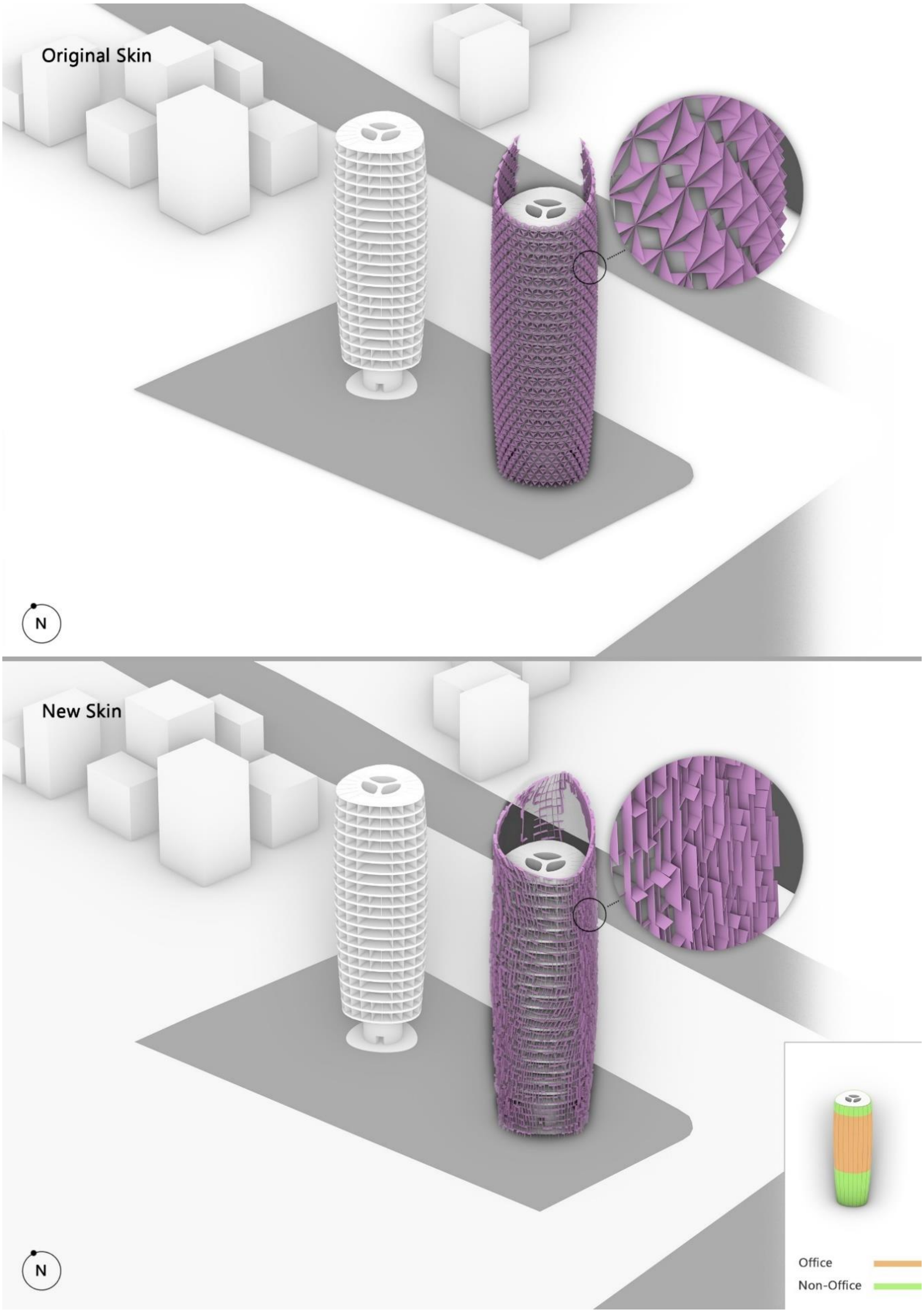


Figure 91 *Al-Bahr towers and egg-crate (crossed) Pattern (before and after)*

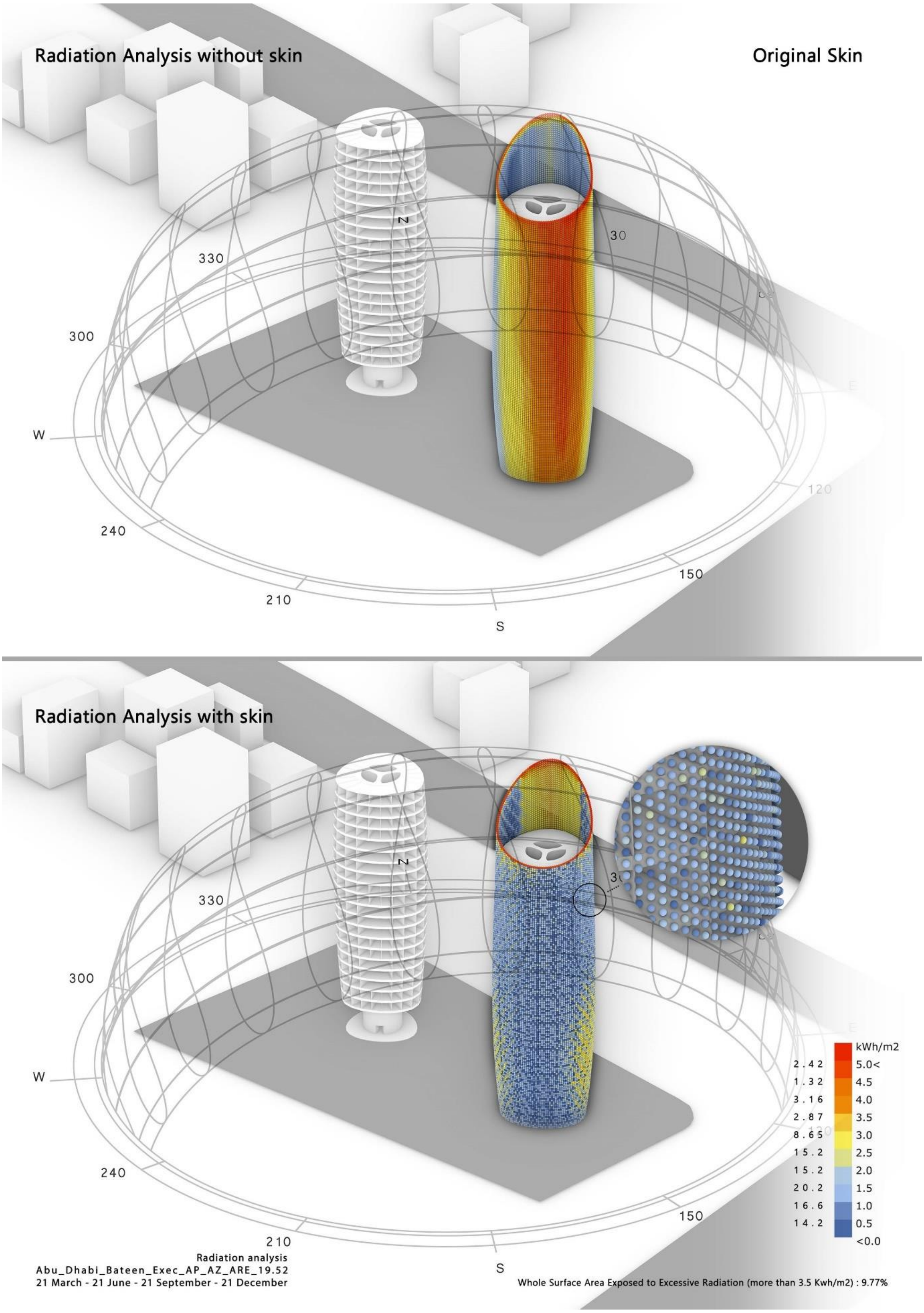


Figure 92 *Radiation Analysis of the Al-Bahr towers and egg-crate (crossed) pattern with the original skin*

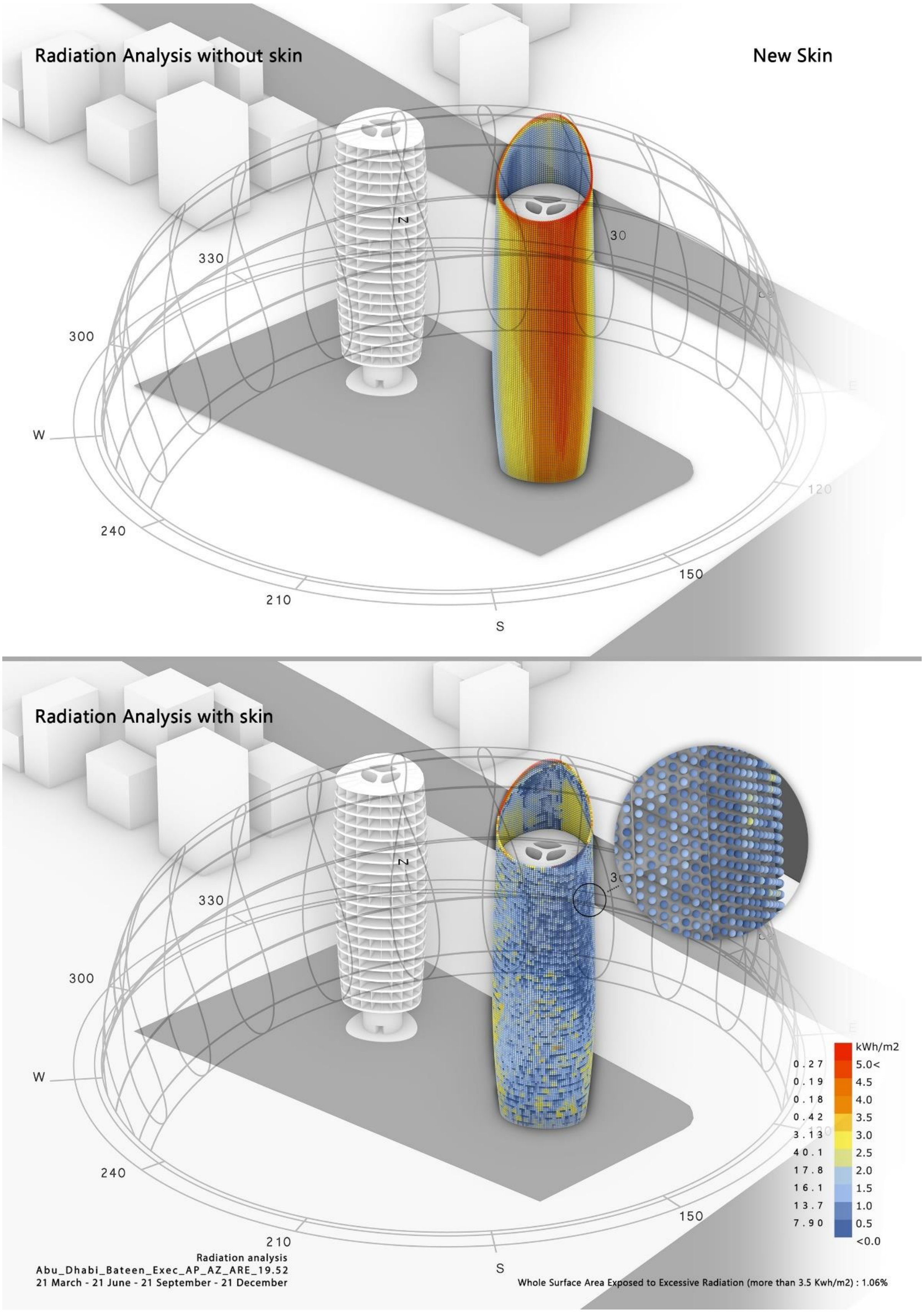


Figure 93 *Radiation Analysis of the Al-Bahr towers and egg-crate (crossed) pattern with the evolved skin*

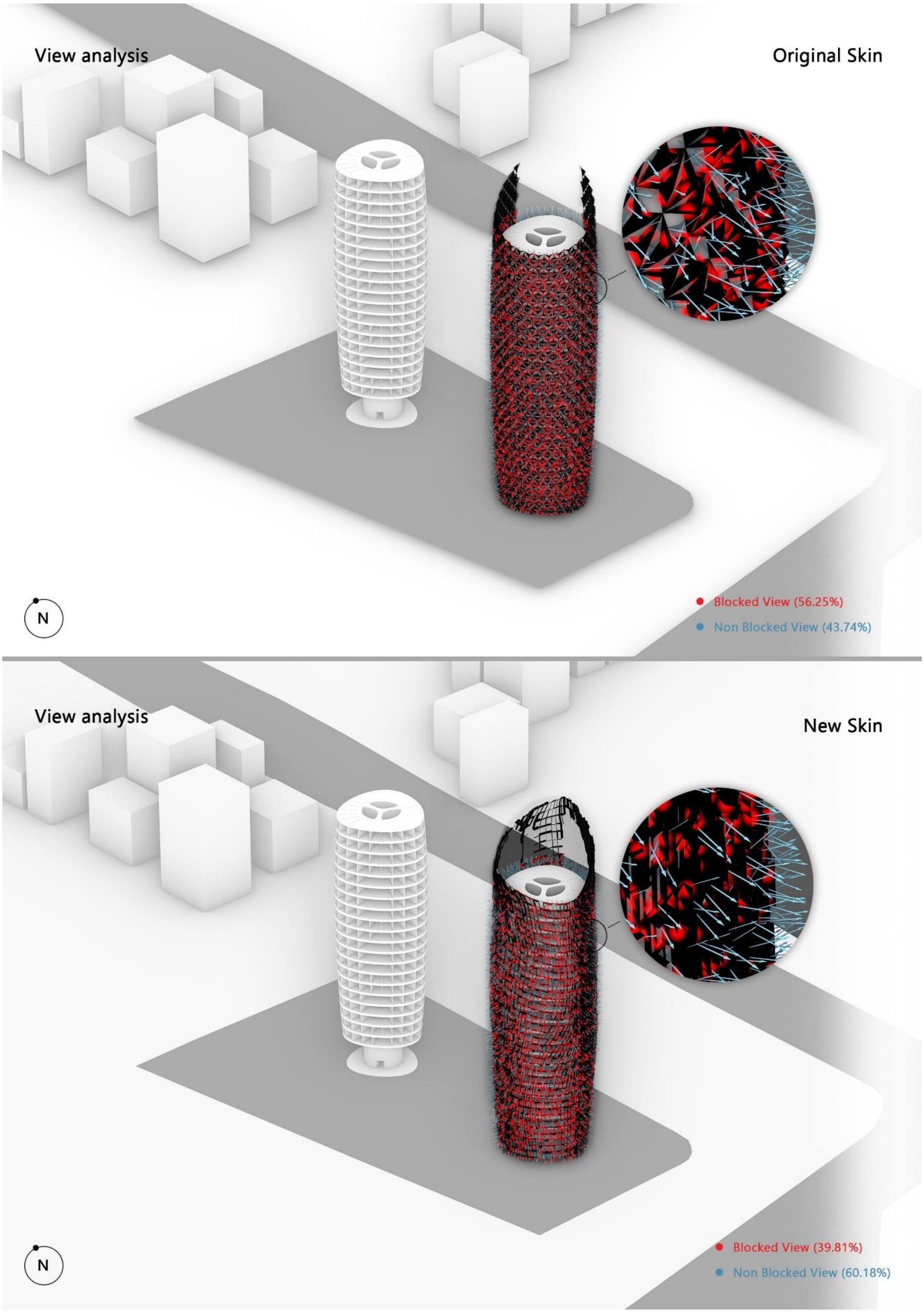


Figure 94 *View Analysis Al-Bahr towers and egg-crate (crossed) pattern*

Evaluation and Results: the Al-Bahr towers with egg-crate (crossed) pattern

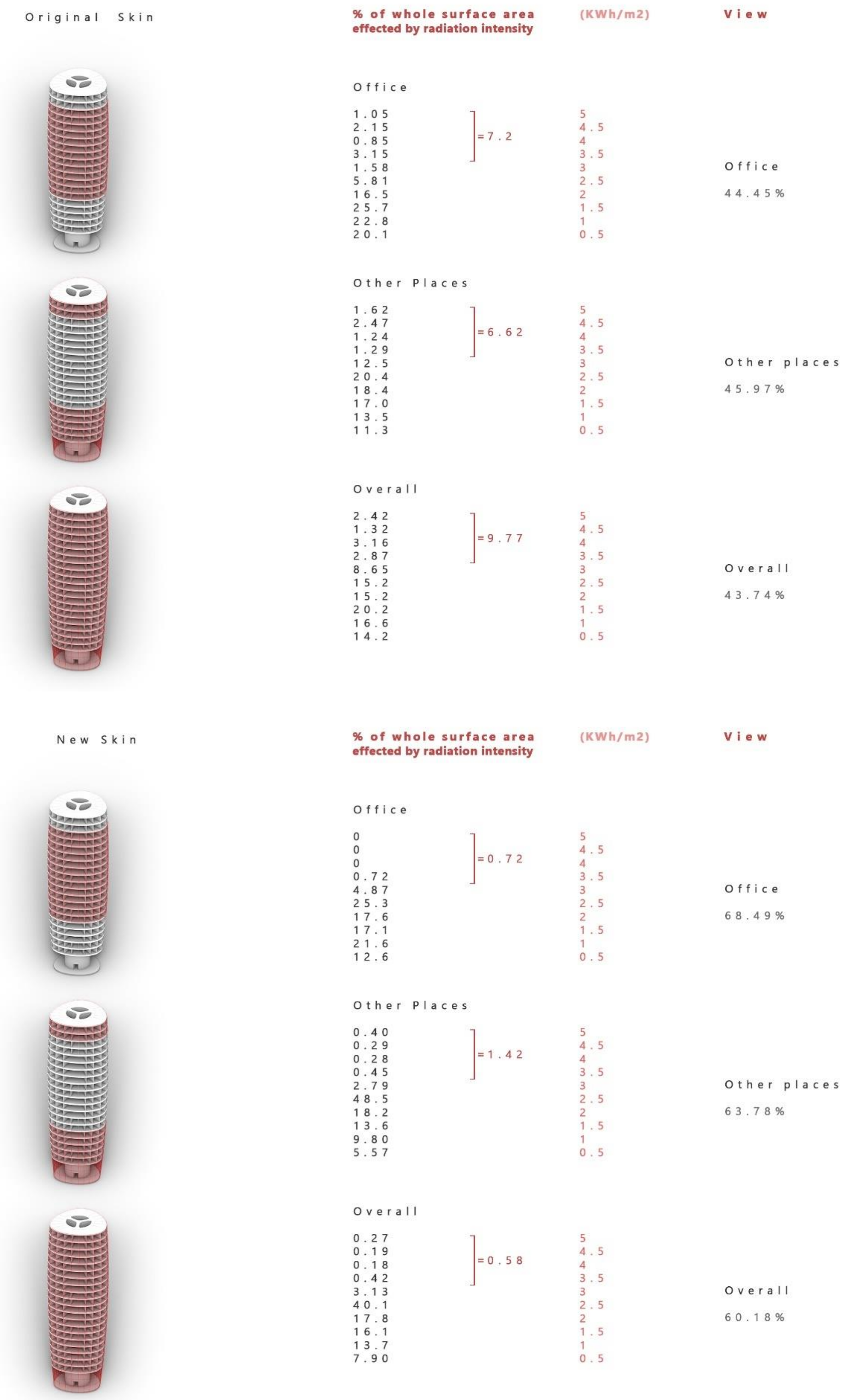


Figure 95 Evaluation and Results: the Al-Bahr towers with egg-crate (crossed) pattern

Optimisation Analysis of the Best Solution of the Al-Bahr towers with egg-crate (crossed) pattern

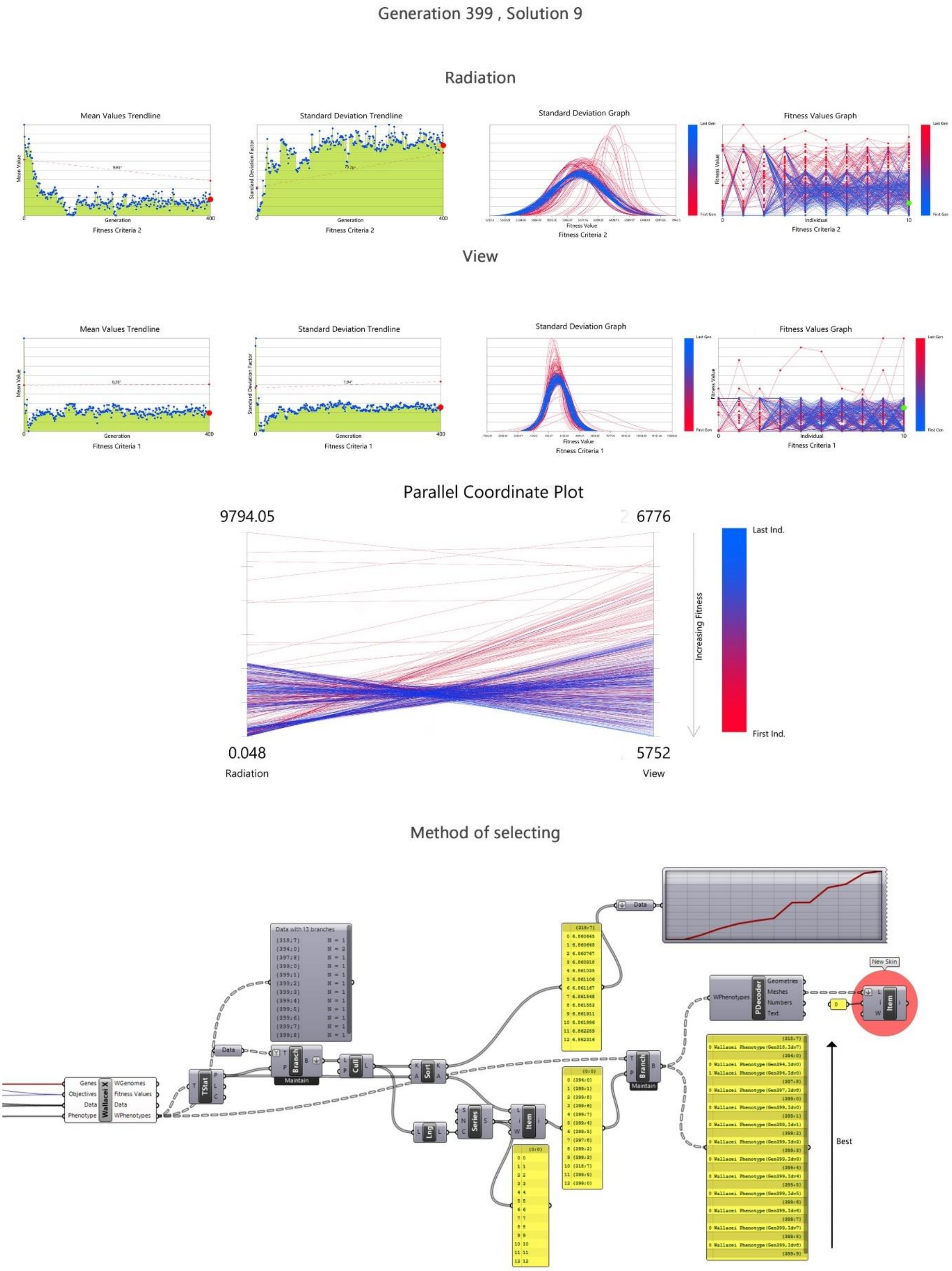


__Figure 96__ Optimisation Graphs of the Best Solution of the Al-Bahr towers with egg-crate (crossed) pattern, Generation 399

4.2 Response to Users' Comfort (Phase II)

This phase of the research presents a simulation tool to evaluate one office floor of Al-Bahr towers in terms of users' thermal comfort with a set of agents representing staff and visitors. The building and the skin in this simulation are modelled based on the previous evolutionary optimisation solutions. Therefore, this simulation aims to make the previously generated solutions (new passive skins) adaptive to users' needs during specific times and periods. The experiment below shows that simulating users' behaviour inside a building provides designers and architects with data about the most used and solar radiation-exposed areas. This allows designers to evaluate their design before implementation.

This phase aims to respond to the users' comfort discussion initially mentioned by introducing an advanced method to bring adaptation to passive shadings in terms of reducing solar radiation. This method will be studied and illustrated on a selected office floor of Al-Bahr towers as a case study which takes place after the previous phase of the skin development process (phase 1). The reason for choosing only one case study for this phase is because of the time and computation power required to run the ABM simulations. However, it is worth mentioning that the proposed method can also be applied to other case studies by simply replacing the floor plan used in the simulation.

This project uses a pedestrian simulation plug-in in Grasshopper called PedSim (Peng, 2019) as the platform to develop the ABM model. In PedSim, People move from Start Gate to Destination Gate, following the best route and avoiding obstacles and other People. If they see a Target of their Interest, they will go to that Target, stay a while and re-route to the Destination Gate. The agents can be mobile (pedestrians, cars, buses etc.) or immobile (buildings, bus stations etc.) (figure 97).

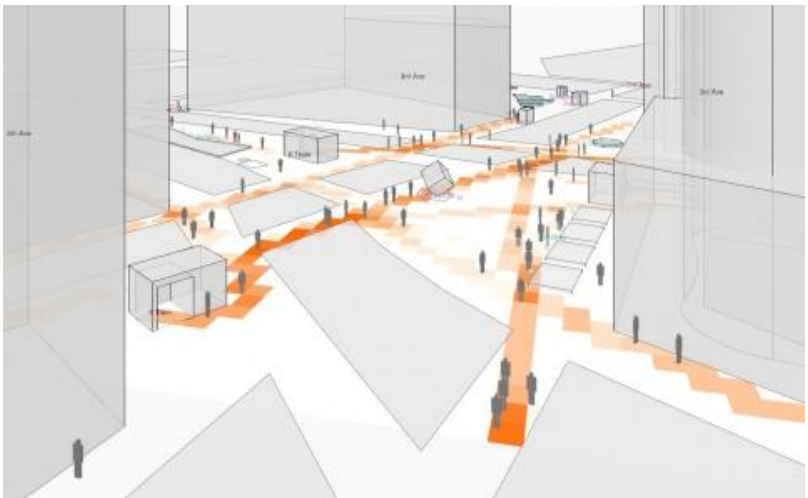


Figure 97 *PedSim pedestrian simulation plug-in in Grasshopper (Peng, 2019)*

This phase of the project is primarily concerned with pedestrian agents as an evaluation tool for optimising and designing the buildings' skin. The areas that the agents spend the most on the floor determine the type of shading the building skin should have in order to take into consideration during the design phase of the facade to maximise the users' thermal and visual comfort. The pedestrian agents in this process are divided into two parts. First, the users that are working in the building and second, visitors who spend a limited period on the building and have access to only a specific part of the floor.

The goal of this experiment is to collect data about the density agents in each area and the amount of time that they spend on a different part of the floor. The orientation of movement and linger time of each agent, based on the type of the agent, is different and is decided randomly by each individual agent from the pre-specified targets.

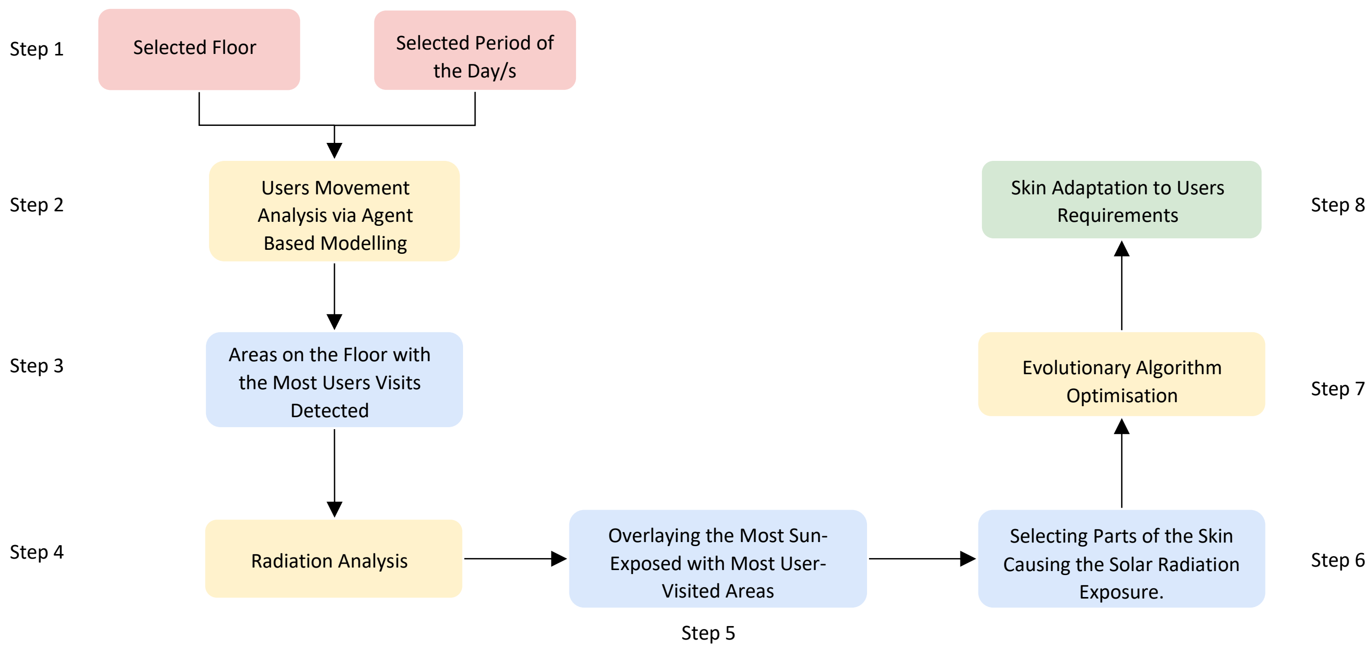


Figure 98 Eight Steps of the ABM process of this research

The period of the day selected for this experiment is the 21st of June, and the solar exposure analysis is calculated from 9 am to 5 pm (office hours).

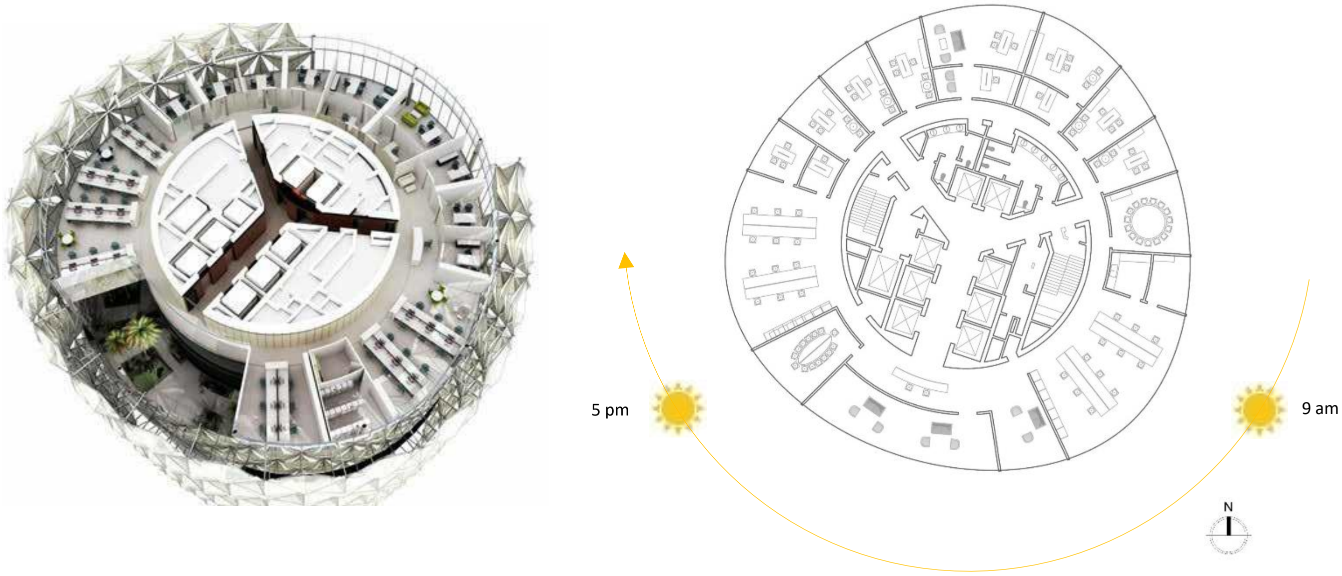


Figure 99 *Solar Exposure Analysis (Armstrong et al., 2013).*

After selecting the floor for the period of the day period, the places where the users (agents) need to be in circulation or working are marked.

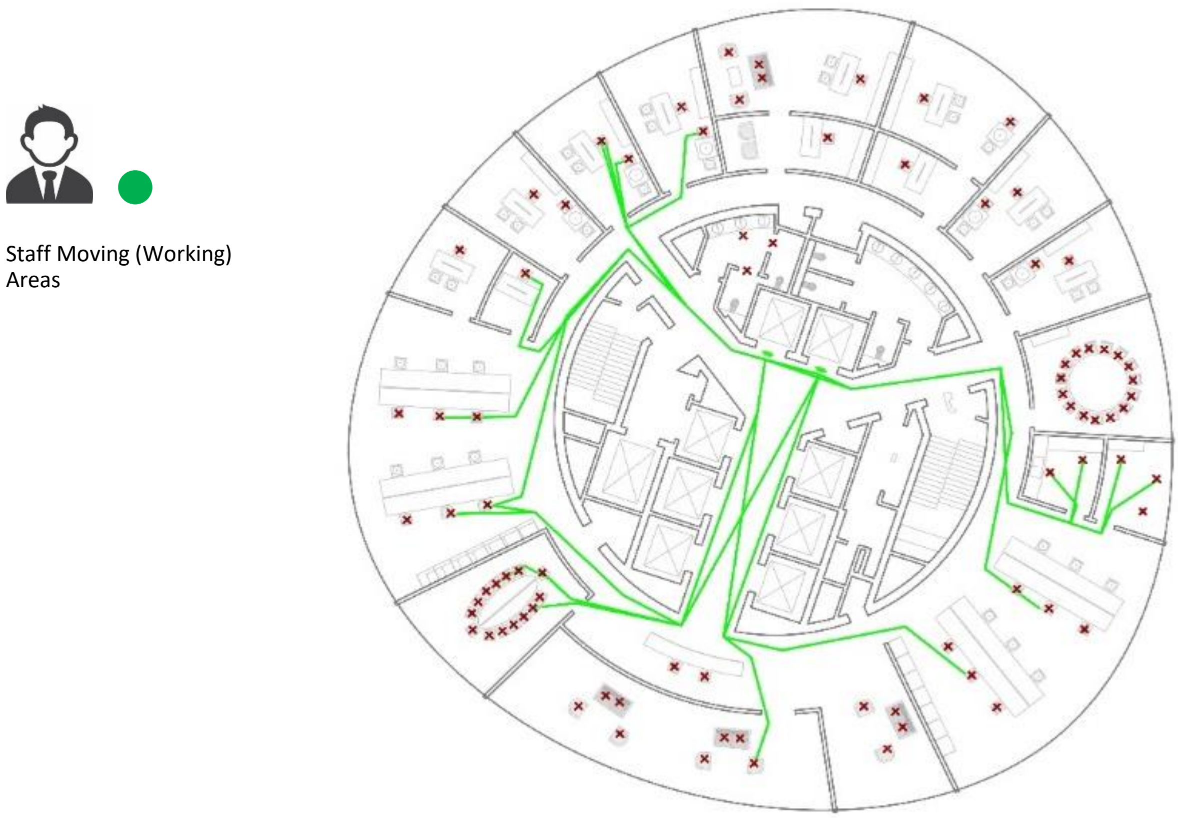
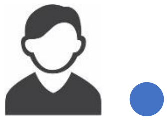


Figure 100 *Staffs visiting (working) areas*



Visitor Moving Areas

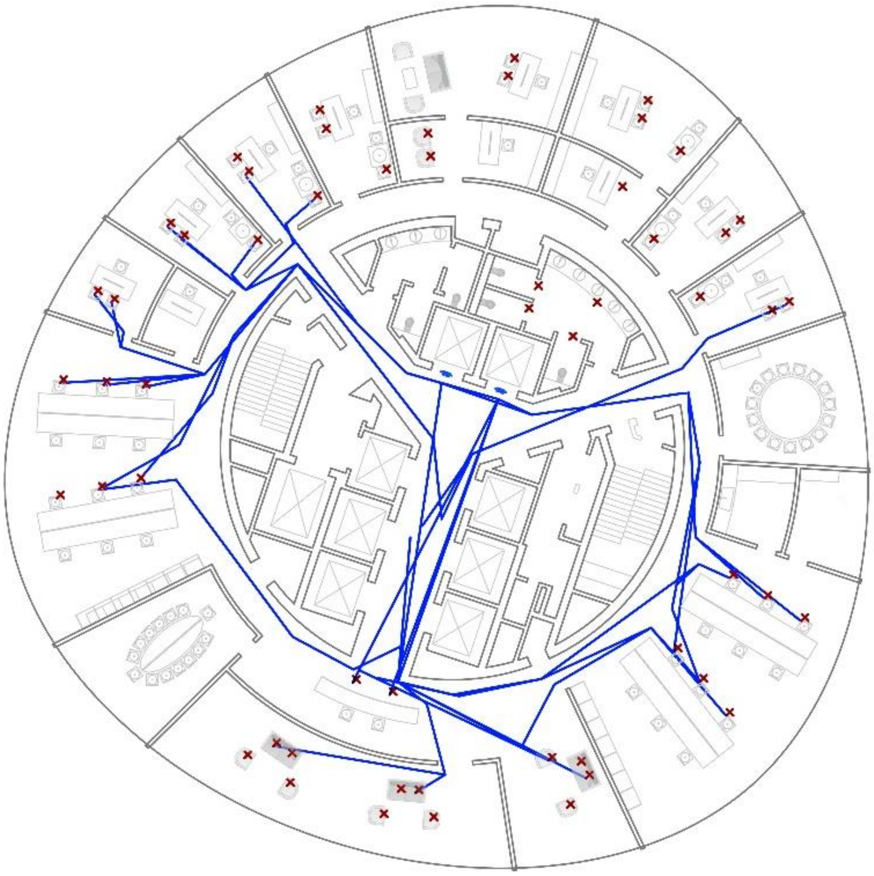


Figure 101 *Visitor moving areas*

After setting targets for the agents,[17] the two groups of visitors and staff were introduced in this simulation in order to detect the most visited and circulated areas on the floor during the office hours. The (ABM[18]) experiment in this research employed Rhinoceros3D, Grasshopper3D and its plugin 'PedSim Pro' (Peng, 2019) to run the simulation and analyse the results thoroughly. The decisions that the agents make during the simulation are based on their role in the building (visitor or staff). As a result, their meeting targets, movements and the time they spend at each location are also depended on their role.

[17] Agents are intelligent machines with the capacity to perceive their surroundings, make choices based on a personal set of preferences, and respond to changing conditions. The agents constantly evaluate their choices in order to respond to their environment. Each agent has a physical body, a brain, and unique abilities (ASCHWANDEN et al., 2012).

[18] An agent-based model (ABM) is a class of computational models used to simulate the behaviour of autonomous agents (individuals or collective entities like organisations or groups), as well as their interactions, in order to evaluate the effects of these behaviours on the system as a whole. It incorporates concepts from evolutionary programming, complex systems, computational sociology, emergence, and game theory. Monte Carlo methods are used to introduce randomness. Particularly within ecology, ABMs are also called individual-based models (IBMs) (Grimm, Railsback 2005)

Users' (visitors and staff) Movement and Activity Heatmap

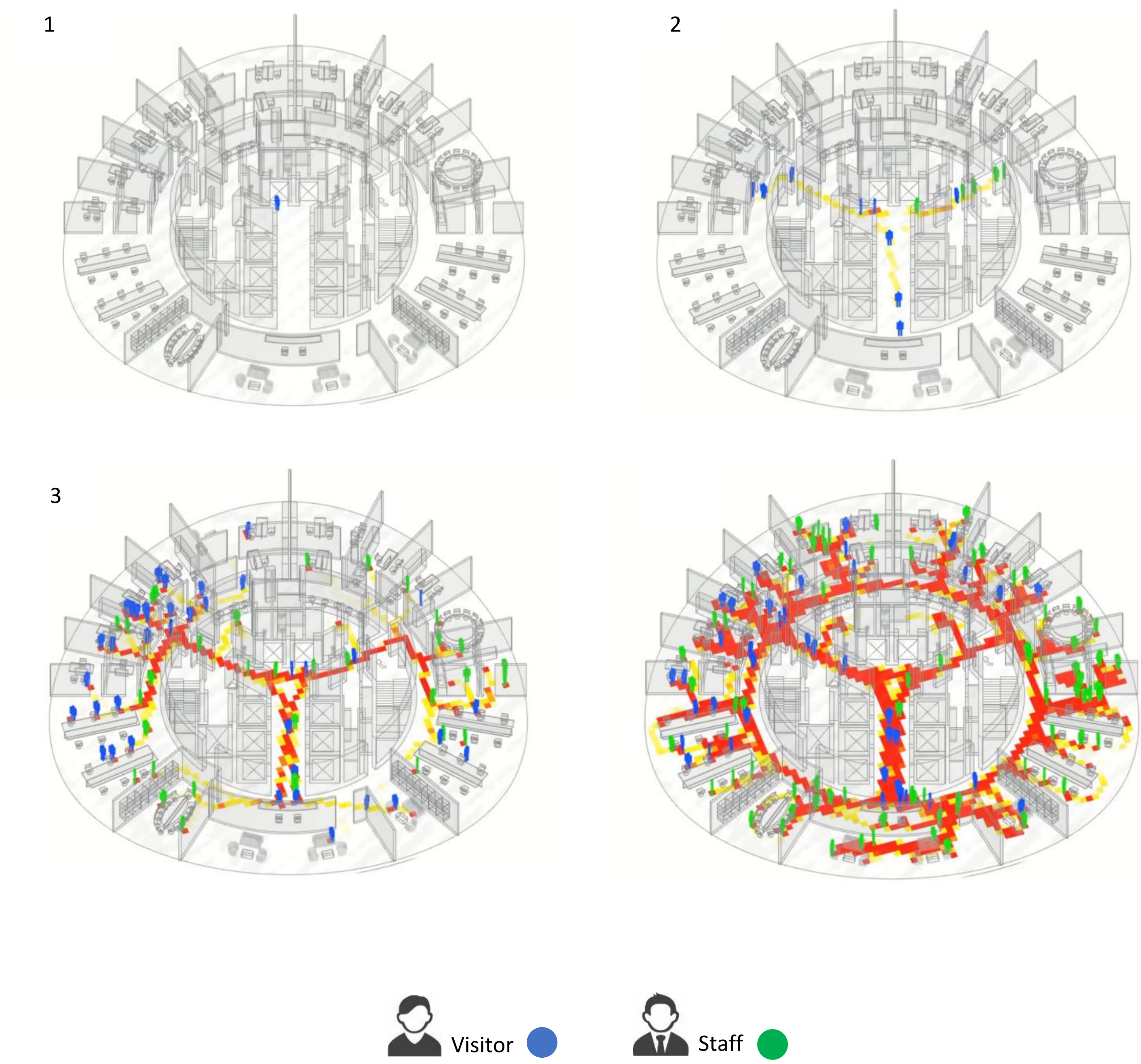


Figure 102 *ABM simulation of the users' movement and activity area from 9 am to 5 pm on the 21st of June. The full video of the simulation is available at:* ***https://vimeo.com/manage/videos/719396423***

High Traffic Areas Detected

Figure 103 *High Traffic Areas Detected*

Radiation Exposure on the Office Floor from 9 pm to 5

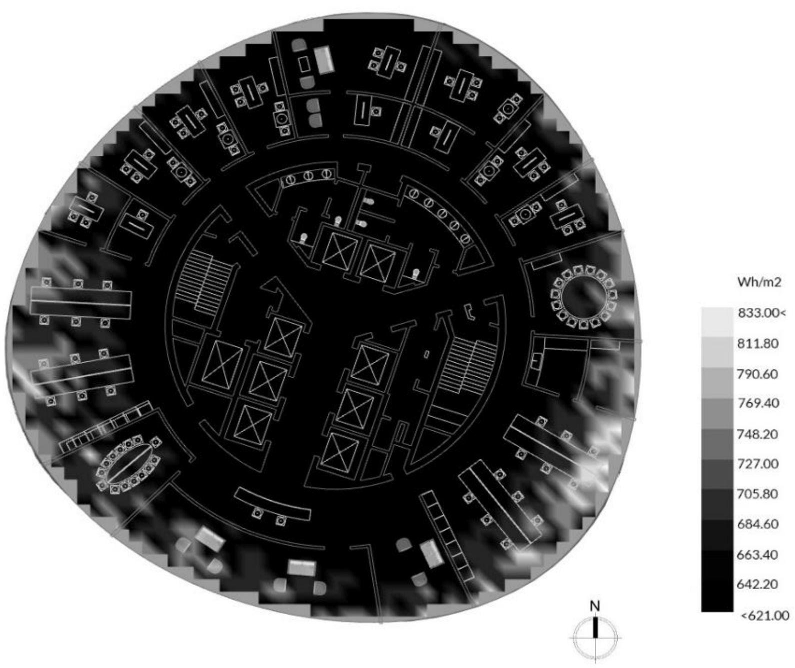


Figure 104 *Radiation Exposure on the Office Floor from 9 pm to 5 pm*

High Traffic Locations Overlaid with Radiated Spots

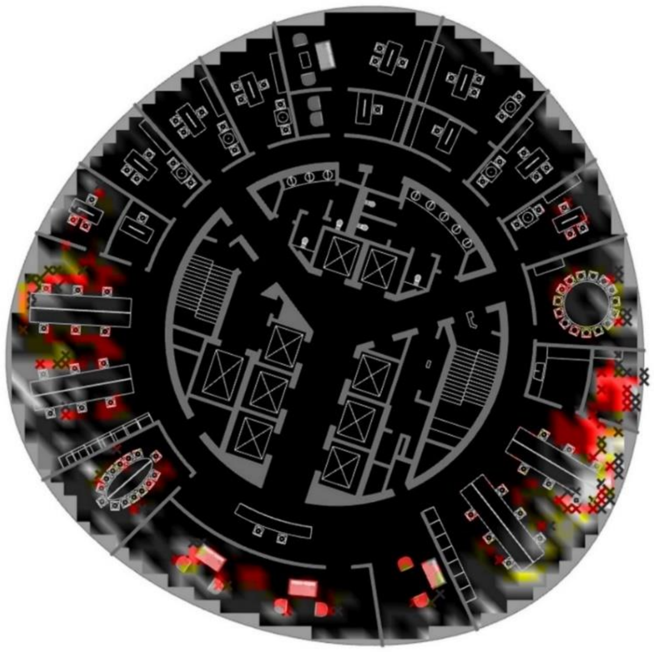


Figure 105 *High Traffic Locations Overlaid with Radiated Spots*

Target Areas Detected Spots From 9 am to 5 pm

Figure 106*: The Most Visited and Radiation Exposed Spots Detected From 9 am to 5 pm*

Cells Responsible for Radiation Exposed on Detected Spots from 9 am to 5 pm in June

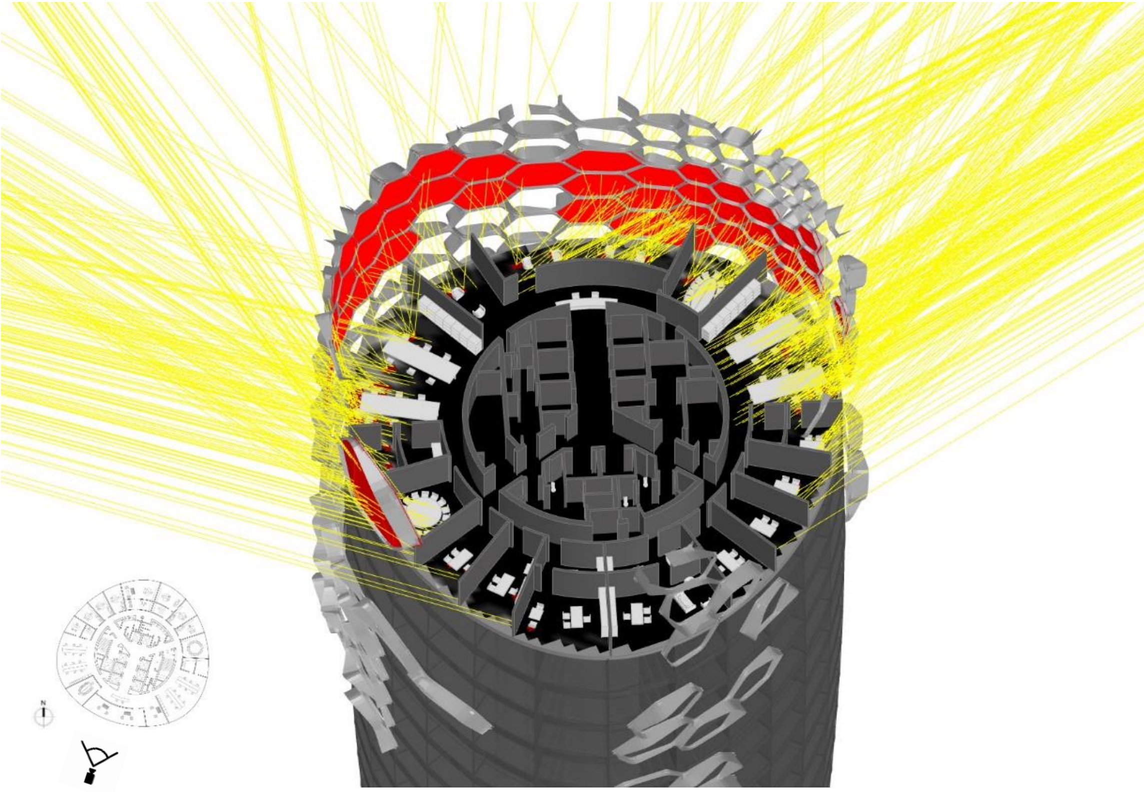


Figure 107 *Illustration of the solar radiation rays going through the specific parts of the skin towards the areas on the floor with the most users' interaction*

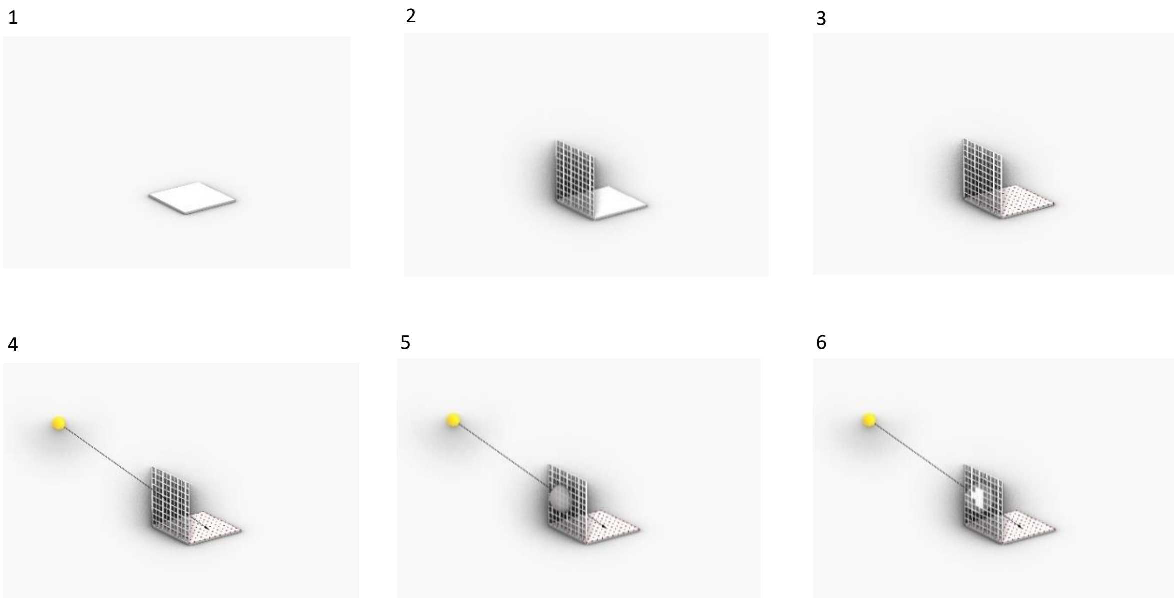


Figure 108 *Method of detecting parts of the skin for adaption*

The method for detecting the parts of the skin that the radiation rays are going through has been detected, as shown above. At the first and the second stage, the skin and the floor have been introduced. In the third stage, the seed points are scattered all over the floor as sensors for detecting rays. In the fourth stage, the solar rays are tracked. And at the fifth stage, the parts of the skin that allow the seed points with most users' presence to be exposed to solar radiation start to form a bubble around themselves. This bubble highlights the parts of the skin that the rays are passing through in order to reach the most user-visited seed points on the ground, which will be used for further optimisation in the research skin adaptation process.

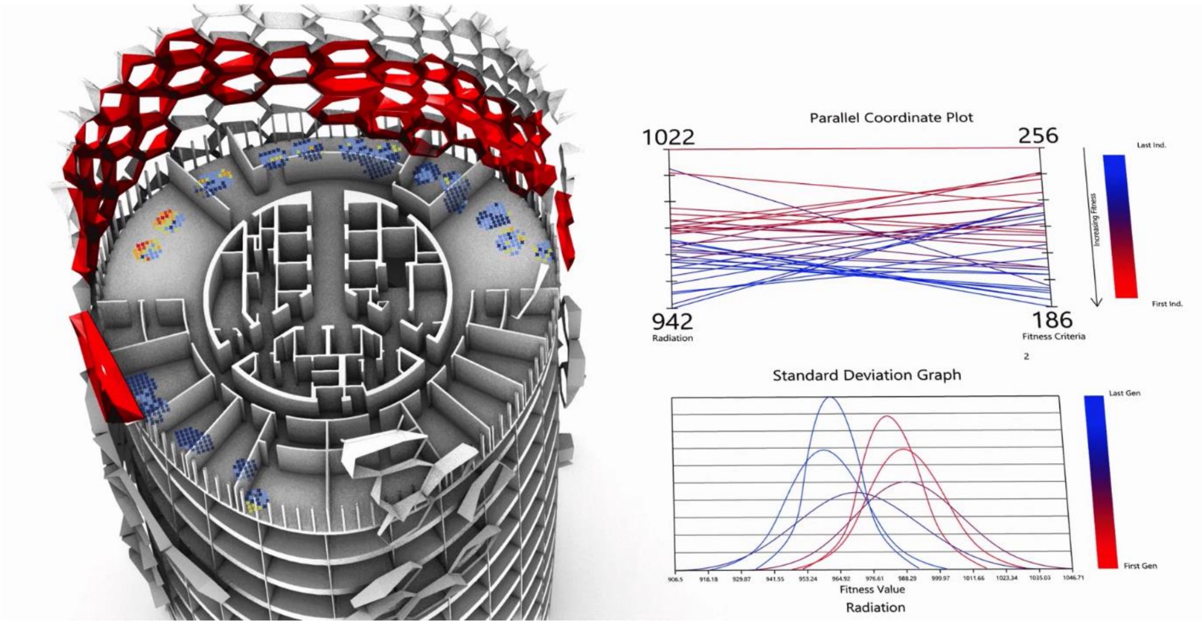


Figure 109 *Skin adaptation process: selected (detected) parts of the skin are taken to the evolutionary optimisation for adaptation to users needs. Animation available at:* [*https://vimeo.com/manage/videos/719396423*](https://vimeo.com/manage/videos/719396423)

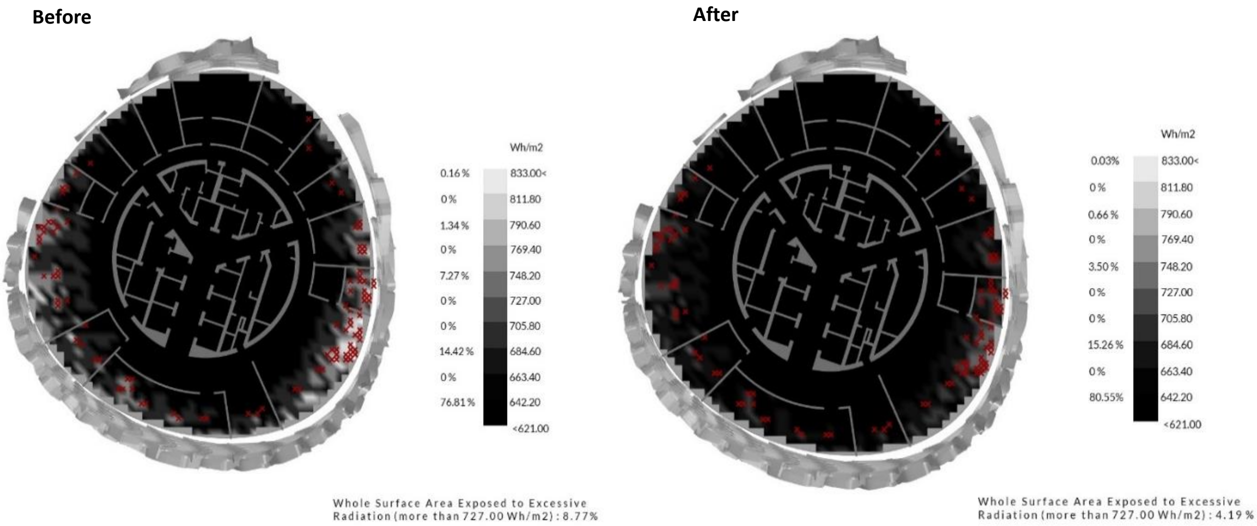


Figure 110 *Areas Exposed to Solar Radiation During 9 am to 5 pm on June 21st*

5 Discussion

The proceedings chapter described a systematic process for implementing a collection of biomimetic principles into experiments via evolutionary design processes to evolve building skin morphological configurations with formal and behavioural properties suitable for adaptation to a variety of different building forms in hot environments. Through a series of analyses (regarding thermal and visual comfort) devised specifically for this research, the experiments looked at how homeostatic principles may be applied to the processes of building skin design.

Four distinct tower forms in two different cities but with similar weather conditions were selected to evaluate the proposed methodologies. PIF towers in Riyadh in Saudi Arabia, Abu Dhabi Market Square, Al Hilal Bank Tower and Al-Bahr towers in Abu Dhabi in the UAE were selected because of their relative differences in forms and morphology. This difference creates a challenging condition for the design experiment to ensure that the research outcome is applicable to different scenarios and building morphologies.

As a result, the experiments were created to address a specific building skin design problem by using evolutionary computing to enable the formation of homeostatic properties across various forms of shadings. All design experiments were carried out to evolve and develop building skin morphologies that fulfil the specific thermal and visual goals considering their environments.

The followings are the abstracted biomimetic behaviours that were included in a group of evolutionary design models. (described in section 4.1.1, figure 43).

- The algorithmic application of a homeostatic process's regulatory mechanism to keep the solar radiation variable in a steady state (less than 3.5 kWh/m2 solar radiation exposure on the building’s surface) throughout the repeated evolution process.
- The algorithmic construction allows the development of morphological characteristics that result from extracted biological adaptation lessons. These formal characteristics include the capability to manage the volume-to-surface ratio using self-shading mechanisms, morphological configurations, and size variations all over the skin.

These morphological attributes are included in the phenotypes by the changes allowed in the genotypes as well as attractor units that can be spread throughout the building surface area to change the density of the skin cells or shadings (figure 41).

The agent-based modelling analysis was conducted to examine a method to respond directly to users' needs in the building. It also helped to spot the most crowded areas that people visit on each floor to ensure that the skin is not evolving for unwanted zones in the building during the generative design process. By doing this, the design process will be focused, optimised, and less time-consuming, leading to generating better solutions.

Seven evolutionary design experiments and one agent-based modelling simulation emphasise the importance of early-stage design exploration before finalising the design and the construction phase. It is concluded that the success rate of retaining a 'good' view while reducing solar rays' variable in the evolutionary design system by adding implementing biomimetic behaviours in the system such as surface-to-volume ratio, self-shading attribute, biological process and evolution and homeostasis principles. The proposed evolutionary design system has freedom and flexibility in exploring solutions with different rates of applicability of the biomimetic elements mentioned above, depending on the effect they have over the view and thermal comfort goals. The effectiveness of the elements brought into the simulation is analysed by:

- Measuring the amount of solar rays that is blocked by the skin.
- The amount of blocked rays that is projected from inside to the outside of the building represents the view of the users. (Section 4.1.4)

Both of these are manifested in the process of analysis and construction of the proposed solutions during the evolutionary design simulation. Hence, the applied technique was investigated case by case, and it was shown that this approach could be used as a universal strategy across many evolutionary models (Analysis pages of section 4.1.4).
The selected towers were chosen carefully due to their difference and complexity of form and their skin arrangement, which is divided into horizontal, vertical, egg-crate (crossed) and cellular type. (Section 2.5.1)

A methodical strategy (figure 42) was developed for this stage by which the part of the building which is exposed to excessive radiation will be capable of generating new morphological attributes which significantly, according to the data (the results pages of section 4.1.4), reduce the excessive radiation (the emergence of biomimetic and homeostatic behaviours). In the seven performed evolutionary designed skin on the selected towers, all analysis method, visual and thermal, proves that after implementing the new morphological attributes through the evolutionary algorithm, the results are

significantly improved to achieve the main goal, which is to maximise blocking the solar rays, while improving the view to the outside. (the result pages of section 4.1.4)
This analysis came to a conclusion that to what extent the proposed evolutionary design system could evolve buildings' skin and obtained solutions for the visual and thermal objectives that acquired high fitness values of adaptability and performance for the form of the building and the location of the selected towers.

The accomplished analysis revealed that the proposed evolutionary design system evolved solutions with morphological configurations that derived from biology leading to higher and better ranks of solutions in terms of their performance for thermal and visual comfort.

The newly applied morphological configurations on the skin of towers emerged from evolutionary simulations with formal attribution taken as an abstraction from homeostatic concepts like high surface-to-volume and high surface-area ratios. The proposed method can help architectural designers and architects perform objective and subjective selection methods on the solutions generated by the evolutionary model during the form finding and early-stage design of towers and buildings in the Persian Gulf and other regions with similar weather conditions. Hence, the evolved skin morphologies with embedded biomimetic adaptive behaviours are called Biomimetic (homeostatic) skin morphologies.

The research was evaluated through a sequence of analyses comprising three elements of thermal analysis, view analysis, and agent-based modelling section. (Section 4.1 & 4.2) Each case study contains two pages of evaluation and analysis that validates the results of the evolutionary computation simulations (Section 4.1.4.1 to 4.1.4.7). These sections of enquiries evaluated the effectiveness of the applied method in three different ways. Investigated the efficacy of the implemented methodology in three parts; the first element of simulation tackled the visual comfort problem. The second element of the analysis proposed a unique way of measuring thermal comfort and minimising unwanted solar rays.

5.1 Response to Research Questions

Below are a restatement of the research questions from section 1.2, along with an explanation of how the research was conducted to address them.

1. How can the combination of the strategies from living organisms, biological processes, and computational design principles be used to design a building skin that can bring thermal and visual comfort to the occupants in compression to conventional ones?

A detailed investigation of the potential adaptation lesson in biology, alongside looking at the BioSkin database in order to find a good source of potential living organisms that can have suitable applicability in architecture, was the cornerstone of a proposed mind map (figure 4); which shapes the evolutionary design system and method developed in the context of this research. The proposed mind map of this research clearly demonstrates how the extracted biological lessons in nature can be used and adapted in disciplines like architecture and computational design.

This research categorised the adopted, biological lessons into the following four parts.

a) Surface-to-Volume Ratio
b) Self-shading Techniques
c) Homeostasis Principals
d) Emergence, Evolution, Growth: Grouping and Partitioning Technique of Stem Cells of Plants

The development of these morphological qualities in skin tissue, which are a manifestation of biological homeostatic behaviours, can be made possible by the algorithmic building of the phenotype and genotype of evolutionary models. In organisms, the adaptation strategy of the above four groups occurs through multiple generations. By mimicking and embedding these attributes in the genes of the new proposed skins, through many generations in the evolutionary design model, the attributes emerge on the new buildings' skin.
In order to address the above research question, this project highlighted the association between the four phenomena above (a, b, c, d) and their combined effects on the evolution of morphological attributes of species. The concepts of species biomimetic behaviours and evolutionary adaptation were put into a series of mathematical loops and used to a generative skin design process.

The evolutionary design models were created by utilising the extracted principles mentioned above in the construction of phenotypes and regulations in genotypes to evolve new skin morphologies on selected parts of buildings in different locations with morphological attributes that, in comparison to the original skin of the buildings, obtained enhanced visual and thermal performances (analysis conducted in Section 4.1.4). The proposed design system successfully evolved skin morphologies sensitive to their context and building form on four different buildings, areas with distinct solar radiation angles.

To determine if the evolving skin morphologies were successful or unsuccessful in generating biomimetic characteristics (that enhance the skin performances), a proposed set of solar radiation and view measurement heat maps was applied over the selected buildings' surfaces, demonstrating the difference in performance before and after applying the biomimetic principles to the skins.

It was observed that the interventions of morphologies applied to the skins impacted the transferred radiation and established an improved radiation gradient and visual comfort level for the buildings with the evolved skin tissues in comparison to the original skins. These morphological implementations were imposed on the skin tissues by applying the following attributes to the genes of the new skins during the evolutionary design process. The ability to change the shadings' length, width, angle of attachment to the building, their grouping and proximity between each other, and their morphological arrangements were obtained from extracted biological lessons and principles.(Section 2.1.2.5)

In Section 4.1, an analysis was conducted to comprehend the relationship between the skin morphologies and solar radiation blockage to explore any emerging biomimetic qualities. Therefore, to analyse and assess the techniques established in this study (and to employ the biomimetic adaptation lessons (principles) in the evolutionary design processes), a proposed homeostatic workflow for the generative models was established and effectively applied to several design scenarios (figure 42). Due to the size and complexity of the design scenarios, the morphological details of the selected buildings' skin were abstracted, leaving just the skin's overall contribution to be taken into account. The previously mentioned morphological implementations left a positive impact on solar radiation blockage and evolved skin tissues across all selected candidates, resulting in elevating the visual and thermal comfort levels of the users in the buildings. Lastly, the study in section 4.14 showed that these qualities emerged in a variety of evolving skin morphologies, as well as their application to the chosen buildings of various forms further proved that these characteristics contributed to the development of biomimetic behaviours.

2. Is it conceivable to develop a design exploration method for designing building skins as an alternative to conventional mass-produced shadings that has the capability to be modified and applied to different buildings with different shapes and forms?

The production of skin morphologies using adapted biological principles necessitates the use of a responsive generative model that comprises a feedback system that enables the assessment, selection, and reconfiguration of the generated design solutions. As a result, the experiments that were presented used an evolutionary biological model as their main design driver (figure 43), in which the biomimetic lessons (collected from the proposed mind map) were analysed, and was conducted with two key techniques for incorporating biomimetic adaptation lessons in an evolutionary design model, as follows:

- The algorithmic construction of a regulatory system to keep a thermal and visual-related variable in a steady state throughout the evolution (using conditional statements to act as homeostasis). This is a phenotypic and genotypic implementation that enables a detecting behaviour and the capacity to undo a change effectively (figure 42).

- The algorithmic implementation of the phenotype allows the development of a collection of morphological attributes that emerge from biological adaption behaviours. These formal attributes include the capability and control over the surface-to-volume ratio, self-shading mechanisms through morphological configurations, size and geometrical changes across different levels of organisation and grouping and partitioning techniques (density variation strategy). This helps divide the skin tissues or shadings based on size and density into various groups in order to be applicable to its context (buildings surface areas with different forms and shapes) with the purpose of maximising the view and minimising solar radiation intake (optimise performance).

The experiments in chapter four's evolutionary design models were successful in emerging new skin tissues with biomimetic adaptation attributes all over the experiment area (selected buildings' surface area that came with different forms and shapes). In order to include a regulatory mechanism inside the iterative process of evolutionary computing, this operation enables the modification of surface-to-volume ratios and self-shading processes, which are crucial morphological characteristics of biological homeostasis.

This was accomplished by specifying two trigger points (Excessive Radiation Exposure of more than 3.5 kWh/m2 to activate HMA[19] and 4 kWh/m2 to activate HMB[20]) purely for the aim of regulating and sustaining solar radiation transmission variable within a specified range during the course of the simulation.

In addition, to determine how the model would react under analysis in relation to the original skin, a separate test was carried out for each case study (without incorporating the biomimetic behaviours). In the Evaluation and Results pages of Section 4.1.4, the success and failure of this strategy were examined by the proposed analysis methods (for thermal and visual comfort) and the in-depth comparisons. It was determined that the flexibility of exploring the design space and the setup of the evolutionary design model (thermal and visual conditions, as well as trigger points to activate morphological interventions for genotypes and phenotypes) are highly dependent on the degree to which this method can be effective. In order to drive the simulation toward evolving these attributes across the selected buildings' surface area, which comes in a variety of forms and shapes, the four key morphological characteristics (extracted from the proposed mind map) were selected to be implemented in the evolutionary design models. These ideas were utilised in the evolutionary models' genotype and phenotype (described in section 4.1.3).

3. Can biological lessons and evolutionary algorithms help the design of the skin in order to solve the conflict of view and heat issue of conventional building shadings?

Section 4.1 (experiment setup) outlined how the extracted biological principles can be applied in the NSGA-II algorithm in order to develop a computational design system that can be utilised for designing different types of buildings' skin. Within every design scenario of case studies, the evolutionary model was developed based on four different mainstream types of building shadings (vertical, horizontal, egg-crate, and cellular shading) and was configured to optimise for a certain set of goals (visual and thermal comfort), which were specific to their locations.

The biomimetic adaptation behaviours built-in into each evolutionary design model were equal across all towers (section 4.1.4), but the parameters and variables obtained from the location and morphological inputs are unique to each tower. These variables are expected to change when used in future implementations on other buildings.

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[19] Homeostasis Mechanism A
[20] Homeostasis Mechanism B

The research carried out in section 4.1.4 demonstrated that the evolutionary simulations across all experiments could effectively meet the skin objectives and produced a population of skin morphologies that iteratively improved their fitness. A successful algorithm in evolutionary computing is one with rising fitness and a low (thin) standard deviation[21]. This is evident in the optimisation analysis pages of sections 4.1.4.1 to 4.1.4.7, which acts as an extra indicator to evaluate the process of optimisation and the performances of visual and thermal comfort of the experiments of this study.

As described in section 4.1 (page 73), a total of seven evolutionary simulations were run to examine the thermal and visual performance of four case studies with different shading systems (vertical, horizontal, crossed, and cellular) based on average seasonal scenarios (winter and summer solstice, spring and autumn equinox) with and without the biomimetic adaptation attributes involved in the simulations and development process of the skin. The evolutionary models successfully demonstrated flexibility and success in results to address a range of changes regarding the buildings' form, location, and time that were explored in-depth in section 4.1.4.

It is important to mention that the comparison of visual and thermal comfort performance among all selected towers was performed between the phenotypes that are evolved (new skins) and the original shadings. As shown in section 4.1.4, in all cases, growth or reduction in size, extrusion and angle of the shadings impacted the thermal or visual comfort across developed morphologies in comparison to the original blocks. This explains that evolved morphologies gained biomimetic adaptation behaviours (homeostasis) to find the regulated balanced design and form of skin that addresses both conflicting objectives of visual and thermal comfort of the users.

4. How can the varying preferences, needs and location of the occupants in the building, considering their thermal and visual comfort, be addressed during the design process of passive building skins?

To ensure the evolved skin morphologies approach response to users' comfort directly, an Agent-Based Modelling technique was necessary apart from the evolutionary model to evaluate whether the skin is affected in the places that are needed and to avoid unnecessary shadings and skin materials on areas that it is not actually needed.

[21] Standard deviation measures a set's variance or dispersion in statistics. When the standard deviation is low (thin), the data are concentrated around the mean; when it is high (fat), the data are widely dispersed (Walker, 1975).

Increased shading extrusion, modification of angle, width and density that obtained a high degree of variation across the evolved skin in order to achieve more self-shading and surface-to-volume ratio, tissues led to a less transition of unwanted radiation into the building when compared to the original blocks. However, blocking unwanted radiation could be conducted for areas in buildings where users would rarely meet. Therefore, a systematic approach was required to detect highly visited spots in the building and direct the evolutionary design platform to only target those areas. This naturally led to attaining a smart and efficient generative design system as well as boosting the effect of biomimetic adaptive behaviours to target the occupants' comfort with more accuracy.

The ABM part of this work (section 4.2) includes a series of assessment and analysis techniques to examine the preceding evolutionary models from various angles. In this section (figure 98), a method of analysing the pathways of staff and visitors on the office floor was developed. In figure 103, a detailed heatmap of users' (staff and visitors) pathways and engagements on the office floor is developed. In figure 105, the most visited pathways and areas are overlayed with those that are receiving excessive solar radiation from 9 am to 5 pm. Figure 108 illustrates the method for outlining the parts of the skin that are responsible for the transition of excessive solar radiation. The overlayed of the users' interaction and solar exposure heatmap map was then taken to the same evolutionary design process as the previous phase to adjust the skin by specifically targeting areas where excessive radiation is not fully blocked.

Additionally, the study in section 4.2 analysed the flexibility of the proposed skin generative design platform in order to be applied to different hour ranges of any day or month of the year. Considering all solar radiation angles and intensity changes, and most visited places as well as users' behaviours during specific periods. In the proposed examined experiment, the selected period was the office hours (9 am to 5 pm) on 21st of June. The evaluation models developed in this research (radiation and view analysis) can be used with a variety of evolutionary models and skin design processes. It equips designers and architects with the information they need to make well-informed decisions while designing building skins specifically.

5.2 Contribution to Knowledge and the Significance of the Research

This study investigated how biomimicry and adaptation lessons in biology affect building skin design. Unlike the mainstream practice in which the shapes and forms of the shadings are replicated all over the buildings' skin, and the comfort level of occupants on the floors are overlooked, this research highlighted the neglected point in the conventional skin design and proposed a new method in which the focus of the buildings' skin design shifts to occupants rather than the overall performance of the building. In this method, the areas of the buildings that occupants visit the most are detected and highlighted and become the focus point of the design methodology. In order to detect and elevate the thermal and visual comfort level of these areas, an innovative approach has been proposed with embedded ABM and evolutionary design techniques.

Through computer experiments reported in Chapter 4, this research suggests that morphological attributes of skin forms should be considered during the early design exploration phase to promote a better view of the outside for the users and blockage of unwanted solar radiation and by, which leads to less consumption of cooling systems and increased energy performance optimisation. This acknowledges the significance of skin morphology, especially in the early design explorations of buildings and towers in their mature forms. In addition, the experiments highlighted the contribution of lessons from nature in shaping optimised building skins. This research emphasises following the proposed data collecting system (discussed in Section 2.1.2.5) in order to find the suitable applicability of adapted lessons in nature for skin tissues.

This research explored the role of biomimicry (biological adaptation lessons) on adaptive behaviours and the design of buildings' skin. In contrast to contemporary, mainstream practice in which the shapes and form of the skin are replicated all over the buildings, and the comfort level of individuals on the floors across the buildings are the areas of focus, this research examined the neglected most-visited areas of the buildings. In order to detect and elevate the thermal and visual comfort level of these areas, an innovative method has been proposed with embedded ABM and evolutionary design techniques.

Through computational experiments, this research argued that attention should be given to the morphological characteristics of skin forms at the early design exploration phase to facilitate a better view of the outside for the users and blockage of unwanted solar radiation and by, which leads to less consumption of cooling systems and increased energy performance optimisation. This recognises the importance of skin morphology, particularly in the early design explorations of buildings and towers at the stage of their mature forms. In addition, the experiments highlighted the contribution of lessons from nature in shaping optimised building skins.

This study looked at how skin tissues' morphological attributes affect the thermal and visual comfort levels of buildings, which in fact, affect how well they can adapt to excessive solar radiation.
This study's investigation includes generative and analytical processes, and during phase one, a unique technique was produced to generate skin morphologies with phenotypic variants that can enhance the visual and thermal comfort level of office floors of the selected buildings.
The second phase of the research experiment developed a workflow to fine-tune the outputted results of the generative process by making sure that the skin reaches the ultimate optimisation level by targeting users' most visited spots in each floor rather than any other spots of the building that are not visited by occupants during working hours.

This research contributed to two primary fields: Architecture (buildings' skin design) and computational design (evolutionary computation) through computational experimentation of biologically driven evolutionary design simulations. It highlighted the significance of biomimetic skin morphologies in the adaptation of buildings to excessive solar radiation through a variety of changes and morphological reconfiguration of the geometries of the skin. Investigations have been performed on the vital biological process of homeostasis, which assures that organisms can adapt to their local environment through interactions. The abstracted genotypic and phenotypic characteristics derived from biological adaptation lessons were applied to a variety of evolutionary models through a series of computational experiments to create a unique generative engine that evolves skin morphologies with embedded biomimetic attributes appropriate for their location and context.

5.2.1 Advancement of Mainstream Passive Shadings.

The findings of this research align with and extend the current body of knowledge of passive shadings and are based on the suggested conclusion of the study on literature.

The conclusion of the research's literature (Section 2.5.4) provided a comprehensive overview of existing studies on passive shadings systems. Unlike passive shadings systems, the commonly used active façade shading systems are typically designed to be responsive to one or several environmental conditions (Lopez et al., 2015). However, due to their significant problems in terms of cost, maintenance and durability, they are not widely used. Al Dakheel and Tabet Aoul (2017).

While many previous works have explored the benefits of using passive shadings in reducing unwanted solar radiation and glare, this research goes beyond mere glare protection and thermal comfort. Instead, it delves into the adaptation lessons of biological organisms, investigating how these principles can be integrated into the design process of building shadings to attempt to produce solutions that can respond to the nine criteria and characteristics they need to have to be improved and considered adaptive.

This approach not only demonstrates the importance and effectiveness of morphological attributes in different types of building shadings but also emphasises the significance of enabling shadings to respond to specific objectives such as view and radiation (users' thermal and visual comfort).

Furthermore, the proposed evolutionary design models presented in this study offer a departure from conventional mass-produced building shadings with repetitive louvres to evolved morphological characteristics that respond to users' thermal and visual needs by utilising computational design (evolutionary optimisation) and agent-based modelling. The research enables the generation of skin morphologies that are tailored to specific building forms, locations, and user needs; the ability to adapt and fine-tune the generated designs to optimise visual and thermal comfort for occupants represents a considerable advancement in building skin design which is one of the most significant issues that designers have to deal with in conventional building shadings (Zvironaite et al., 2014).

In addition to its contribution to existing literature, this research advances the field of building skin design by offering a systematic and innovative approach. The integration of homeostatic principles and morphological attributes in the design process leads to the emergence of biomimetic behaviours within the building skins. This dynamic adaptation to solar radiation and user comfort showcases the potential for using evolutionary computation as a powerful tool for the design process in architecture, specifically building skin design.

Overall, this research presents a compelling argument for considering morphological configurations and adaptive behaviours in building skin design. Unlike the existing mainstream shading systems, which lack the ability to respond to constant-changing solar radiation angles and users' needs (Prowler 2016), The proposed design system and its focus on occupants' comfort, solar radiation blockage, and visual performance demonstrate the potential for creating building skins that respond passively, yet intelligently, to their environments, marking a significant advancement in the field and making a valuable addition to the existing literature on biomimicry and architecture and computational design.

5.2.2 Buildings’ Skin Design

The proposed computational procedure was employed in several buildings in different locations with excessive hot weather conditions to illustrate how the suggested techniques may be used to solve a number of skin design challenges (explained in sections 2.5.3). This research investigated the importance of building skins that divide the interior and exterior environments of a building and their impact on the solar radiation transition and view of the user to the outside.

This research builds a bridge from the discipline of Architecture (outlined in Section 1.3.1) to Biology (biomimicry) (outlined in Section 2.1) to explore the possibility of applying morphological attributes throughout the evolution of skin systems (section 3.1). It also argues that data collection and lesson adaptation in architecture should not be limited to copying and inspiring from the forms of the organisms. The evolution process of species in nature occurs over millions of years. The idea of inspiration is that nature has progressed from a formal metaphor to a collection of interconnected dynamic processes that are open to analysis and simulation, as evidenced by the differences between the revised and original editions of Steadman's 1979 book "The Evolution of Designs: Biological Analogy in Architecture and Applied Arts." In the past two decades, "seeking insights at deeper levels into biological processes, from which designers might derive models and methods" has accelerated (Steadman, 2008a, p. XV). Two concurrent events are the cause of this. One is the introduction of computer-aided design into routine practice. And second is environmental awareness and the growing understanding that architecture must learn from both organic forms and natural systems and processes are the first (Steadman, 2008a).

This study discusses that the formal organisation and morphology distributions on building skin should receive greater attention. It highlights that the evolution of biomimetic behaviours throughout building skin could develop special characteristics that provide comfort to users (such as positive impacts on visual and thermal comfort) would be achieved. This research contributes to the lineage of mainstream and mass-produced skin and facade shading proposals of modern buildings (built in the 20th and early 21st century) and highlights the relationship between morphological configurations of skin tissues and the users' thermal and visual comfort. This relationship was studied in the context of commercial towers located in extremely hot weather in the Persian Gulf region.

Furthermore, this study foregrounds the importance of building skin design exploration and their effect on resolving environmental issues such as extreme solar radiation. The investigation undertaken in section 4.1.4 covered this topic objectively and determined that biomimetic morphological configuration has a beneficial impact on prolonging the adaptive behaviours of skin tissues in comparison to their simpler mainstream building shading counterparts.

5.2.3 Morphological Attributes and Adaptation of Skin Tissues as a Biological Argument

This study claims that the adaptive behaviours and morphological attributes of building skin tissues evolve according to the same morphological configurations and principles of adaptation of species (on collective and individual levels) within the context of various environmental conditions in nature. It is without dispute that biological organisms' morphological characteristics have an impact on their adaptations through time.

Homeostatic processes within a particular life span, individually or collectively, are accountable for short-term adaptive and response behaviours; however, evolutionary adaptation takes place over a long period of time (section 2.1.2.3). This study indicates that the implementation of the concepts underlying the selected adaptation lessons in biomimicry and development in the design of skin tissues results in the emergence of building shadings; their morphological attributes enable them to develop adaptive behaviours in a variety of contexts. This idea was investigated and reviewed by the experiments described (chapter 4); this hypothesis was investigated and established throughout an extremely hot environmental conditions, and buildings’ forms and shapes, in Abu Dhabi in UAE and Riyadh in Saudi Arabia. Skin morphologies that were generated from the proposed design system demonstrated a wider variety of environmental performances than their conventionally simple counterpart building shadings. This was confirmed by the study done in section 4.1.4, where the sole variable being investigated was the skin morphology of the buildings' office spaces. These investigations confirmed the influence of the biomimetic morphological attributes of skin tissues on the office floors of the chosen buildings that improved the tissues' adaptive behaviours.

5.2.4 Building Skin Variants Via Evolution of Morphological Interventions

The biomimetic morphological interventions (implementing the morphological attributes) on the original shadings of the selected buildings identified the importance of phenotype and genotype construction in directing the simulation toward the formation of desirable and adaptive morphological characteristics (described in the experiment setup, section 4.1). Additionally, it was determined that formal variations across the tissue and the ability to control the surface-to-volume ratio and shadings density were effective morphological characteristics that could enable dynamic response (homeostatic behaviours) to maximise users' visual and thermal comfort during the skin design process (as demonstrated in the results pages in section 4.1.4.).

This procedure enabled higher surface-to-volume ratios, self-shading processes, and varying densities over the surface areas of buildings. Due to the locational variations and the original shadings form of the case studies, throughout each experiment, the biomimetic morphological interventions developed a unique morphological configuration throughout the skin tissues. Moreover, all experiments showed that the utilised strategy was a reliable means of generating morphological variations throughout the building surface areas.

This study claims that a vast amount of skin variation may be developed in the surface area of the buildings by implementing biomimetic morphological interventions (explained in Section 3.3.3) on the original shadings of buildings in evolutionary design simulation. As a result, skin tissues with a great degree of variety in size, extrusion, and density spontaneously form. The emergence of such variations in shading on buildings contributes to enhancing the adaptability of the skin tissue to a wider range of changes, analogous to biology, where greater species variety enables a greater adaptation of a whole. As opposed to the stereotypical shading systems of contemporary buildings, this study attributes a significant weight to morphological variations (as a result of extracted biomimetic adaptation lessons) in the effectiveness of a design strategy to obtain enhanced adaptation attributes when environmental changes are contingent upon.

5.2.5 Users Comfort

The contribution of the research in the analysis and improvement of visual and thermal comfort in design is 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. To address the concern regarding the blockage of the view from inside of the buildings towards outside. This process has been introduced to the evolutionary simulation as the second objective to increase the view from inside to outside. The view analysis operates based on the several centre points of each room on the office floors of the selected building (demonstrated in section 4.1.2 and appendix II).

5.2.6 Users movements and agent-based modelling:

This study made an attempt to integrate the principles of agent-based modelling with the evolutionary design procedures to improve their effectiveness in evolving heat and view-sensitive skin morphologies. As previously discussed in chapter 4, the entirety of the design experiment simulations in this research fall into two categories of evolutionary design and agent-based modelling.

Additionally, this study developed ways to use the ABM toolkit with the evolutionary design processes and demonstrated how they improved the performance of evolutionary-produced solutions. (investigated in section 4.2). This method successfully created solutions that showed significant improvement in blocking solar radiation in a smart and efficient way by targeting the most visited office floor areas. By comparing the proposed simulation pairs of before and after across all experiments, it is determined that the success of the employed method is high.

5.2.7 Evolutionary Design Thinking: Analysing, Evaluating and Selection

In contrast to typological thinking, this study is centred on population thinking and solving complex issues with various conflicting aims (thermal and visual comfort). Section 2.1.3 shed light on how the population thinking principles are derived from Darwin's contributions to evolutionary thinking. This study suggests the requirement to shift focus away from the design of the solution towards the design of the problem that in relation to it, the use of evolutionary computation strategies produces a generation of suitable design solutions. Multiple objectives are often in conflict with one another in building skin problems. This research has shown that the developed method for addressing complex building design (skin) problems is extremely relevant. It is crucial to use evolutionary computation efficiently to solve complex problems, in this case, the buildings' skin issues. This shifts the method of identifying a single solution based on user preferences with one that places more emphasis on the quantity of design outputs.

It is important to note that the distinction between a group and a single solution does not negate the point that many design problems need one solution. Selection and evaluating tactics are crucial actions in designing solutions to design problems. They provide the user with the knowledge they need to make decisions that are informed. This study produced a complete series of selection and analysis strategies that were used to narrow down the potential design results to a small number of candidates and then to create only one solution for more evaluations (section 4.1.2). The evolutionary experiments of this research have also been evaluated based on a statistical analysis of evolutionary simulation data and independent measurement criteria for each individual (graphs of solutions, section 4.1.4). This series of selection and evaluation procedures can be utilised in the process of many evolutionary design approaches, where screening design outputs and making informed choices are important steps.

5.3 Future Works and the Limitations

The following is a list of the research's noted limitations and some suggested solutions that shape the research's future stages and further studies.

Increasing the Skin Resolution of the Development

This study looked at how to include biomimetic adaptation lessons into the early stages of design explorations to generate building skin morphologies with improved performance towards boosting users' comfort across office spaces' surface areas. It was found that the performance of the design solutions at later phases is significantly influenced by the early design exploration. This study highlighted the significance of morphological characteristics in the early phases of design. Although the skin morphologies examined in this research were resolved morphologically and organisationally, they were still in the initial design exploration stage; the effect of factors such as complexity of the skin morphologies, size variation based on the materials, study and maintenance cost, and economic feasibility of application of the proposed skins within the context of this research, were left to be explored. 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. This is readily accomplished by lowering the requirement for geometrical representations and placing a greater emphasis on data-related phenotypes. This provides the basis for the next series of assessments to be carried out by the author to utilise the suggested method in building skin optimisation scenarios. The scenarios include more detail on each building's skin morphological configurations, as well as their material and details.

Increasing the Area of Investigations

This study assessed the evolved building skins in different locations with varying solar radiation intensities. To investigate the generated skin tissues about any emerging biomimetic and adaptive characteristics, two locations with excessive hot weather were selected as the study regions to analyse their solar radiation exposure at four days in winter, summer, spring and autumn (at seasonal solstices and equinox). The data gathered from these simulations provided a broad view of radiation intensity throughout the investigating areas (office floors) during the day, according to which the behaviours of biomimicry and adaptation were identified and derived. However, because it takes time and resources to run solar radiation and view analysis simulations, the simulations and analysis were restricted to office floors. The author aims to expand the thermal and visual analysis and simulation to all floors across the buildings to deliver a more viable illustration of biomimetic and adaptation behaviours throughout all floors in the selected building. Two strategies will be investigated in order to accomplish this. The first step is to build a well-organised and clean 3D model in an efficient way to simplify the mesh models so they may be fed into the evolutionary design and ABM simulation operations. The second step is to use machine learning techniques to create a model that, based on previously completed simulations, predicts the variations in solar radiation and biomimetic behaviours of new skin forms and topologies. It is worth stating that the analysis techniques in the evolutionary models of this research may be utilised in the design exploration of other buildings with different objectives (described in Appendix I).

Further considerations: Building Function and Material types During the Simulations and Prototype Development

The variables taken into account for simulations conducted in this research were the visibility and the solar radiation parameters. 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 facilitated to ensure the results only reflect the impact of skin morphology on solar radiation intake of office spaces at the selected buildings.

The goal of this research was the relative comparison between different scenarios (shading types and buildings' locations) to identify and emphasise how morphology influences any emerging adaptive behaviours. However, when the results for each scenario become less accurate and may diverge from those of this research, the material, function, and quality of the building's zones are changed throughout the simulation. 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.

Furthermore, another potential path to expand this research is to incorporate the variables such as energy flow, the temperature of the rooms and material studies by developing prototypes and adopting digital twin[22] techniques.

[22] A digital twin is a virtual representation that serves as the real-time digital counterpart of a physical object or process

6 Conclusion and Reflections

Throughout this PhD thesis, the main aim has been to explore and demonstrate the benefits of integration of biomimicry and computational design to revolutionise the design of future building shadings by implementing machine learning (Evolutionary Algorithm techniques) in order to address environmental challenges such as solar heat transmission control and enhancing occupant comfort in extremely hot climates.

Extreme solar radiation in areas such as the Persian Gulf region leads to the employment of expensive temperature regulatory mechanisms within the buildings, which in fact, contribute to extreme energy usage. This excessive use of energy directly or indirectly influences CO2 emissions and subsequently causes temperature rise and global warming.

Species, throughout the course of their evolution, have evolved unique *responsive* behaviours, processes, and formal characteristics that enable their survival and adaptation to sudden environmental changes. This study, through investigations on the biological principles and means by which species adapt to the extreme environmental conditions, put forward a design methodology which highlights the significance of early design explorations in addressing climatic stresses.

The presented experiment in this study demonstrates an evolutionary design system with additional hardcoded regulatory mechanisms to generate building skins with morphological attributes suitable to adapt to the excessive solar radiation of the Persian Gulf region. Homeostasis as a regulatory mechanism and a 'reference point for change' (figure 40) mapped algorithmically into the evolutionary design system to steer the simulation toward generating morphological attributes embedded in the phenotypes that contribute to their adaptation to the excessive solar radiation.

The four case studies, due to the extreme environment they are located in and the use of contemporary temperature regulatory mechanisms, were chosen as the case studies and reference points for conducting comparisons. As presented in section 4.1.4, the evolutionary design process successfully generated candidate solutions with diverse morphological characteristics, each of which performed better in the described measurement criteria in comparison to the case studies. This design methodology emphasises the significance of the skin resulting from the early design explorations in the adaptation to the environment. The employed design system, however, produced a significant amount of variations from which a noticeable number of them are performing better than the case studies.

The discussion of this research outlined a thorough process for attempting to put a collection of fundamentals extracted from biological adaptation lessons to work in evolutionary design procedures in order to develop skin morphological configurations that have adaptive formal and attributes qualities appropriate for four different case studies in the Persian Gulf region. Through a series of studies that was entirely produced via the proposed mind map in this research, the experiments carried out in chapter four evaluated the use of various biomimetic adaptation lessons in the evolutionary design procedures.

Seven distinct design scenarios in three different contexts in the Persian Gulf region were chosen to evaluate the proposed methods. PIF towers in Riyadh in Saudi Arabia, Abu Dhabi Market Square, Al Hilal Bank Tower and Al-Bahr Towers in Abu Dhabi in the UAE were selected because of their morphology and form relative discrepancies.

In order to enable the emergence of biomimetic attributes throughout the office floors of the buildings, the experiments were developed to address a specific design problem through the use of evolutionary computation. To develop skin morphologies that meet a specific set of thermal and view objectives specific to their building, all design experiments were carried out.

The algorithmic application of a homeostatic process's regulatory mechanism to sustain an optimum level of thermal radiation and view range remained in a stable condition throughout the iterative evolution process (figure 42). The phenotype's algorithmic development allows for the formation of a collection of morphological attributes manifested from biomimetic adaptation behaviours in biology extracted from the proposed mind map. These formal attributes are listed below.

a) Surface-to-Volume Ratio

b) Self-shading Techniques

c) Homeostasis Principals

d) Emergence, Evolution, Growth: Grouping and Partitioning Technique of Stem Cells of Plants

The implemented method introduced in the first phase of the simulation of this study was set to maintain the given variables of solar radiation intensity and visual comfort of the occupants within an optimal range (homeostasis behaviour in comparison to the original skins of the case studies. Throughout all solutions presented in section 4.1.4, the thermal and visual comfort of all proposed skins were improved significantly in comparison to the original skins.

The results of the analysis of the simulations highlight the significance of the biomimetic morphological configuration and the relatively diverse relationships between different fitness objectives in the effectiveness of selecting solutions for this approach. The analysis that was done on seven evolutionary simulations on four different case studies emphasises the importance of biological adaptation lessons in regulating the excessive radiation when used in the construction of the phenotypes as part of the genes during the evolutionary development method. It is concluded that the morphology should carry the genes that make them adaptable to the environment in which they are planned to be built. The proposed skin tissues over the case studies evolved in the developed evolutionary model significantly improved the thermal and visual comfort performance of the office floors of the buildings (explained in the evaluations and results pages of the experiments in section 4.1.4). A set of rules and regulations were implemented into the generative models of experiments to act as an abstraction of the concept of coordinated actions of individuals in order to develop such an evolutionary model within which the individual building shadings arise in synchrony. In the phenotype and genotype of the studies, these principles and rules were integrated (section 4.1.3).

The presented simulations illustrated the thermal and visual comfort of all floors overall and specifically the office floors (that were measured and mapped in percentage (shown in the evaluation and analysis pages of section 4.1.4) significantly improved after running the shadings through the proposed evolutionary platform by evolving them and generating new solutions with improved thermal and visual comfort performance.

The second phase studied a deeper level of thermal comfort by focusing on users' movement throughout a selected office floor of Albahr tower. The reason for choosing only one case study for this phase is because of the time and computation power required to run the ABM simulations. However, it is worth mentioning that the method is flexible enough to be applicable to other case studies by simply replacing the floor plan used in the simulation. The ABM simulation revealed the paths of the visitors and the staff in the building. This information is valuable to ensure that during the optimisation process, the evolutionary engine performs in an efficient way by targeting the areas that are only needed for the occupants in order to have improved thermal and visual comfort. Considering this efficiency during the optimisation process also helps the optimisation time as there will be a reduced amount of areas of analysis by focusing on specifically marked areas rather than all surfaces of the floor plans.

Further analysis could be undertaken to determine to what extent this is an effective mechanism to incorporate homeostatic behaviour in design processes. Authors are currently continuing their research in generating a design methodology to better employ feedback and regulatory mechanisms into the generative design processes to explore further morphological variations and their adaptations to the environment. Future work will also study the effectiveness of such mechanism in adapting to the changing environmental condition; the presented experiment considered the solar radiation on seasonal solstices and equinox; on the 21st of June, September, December and March; however, it is worth investigating the dynamic environmental conditions in the simulation. The authors are also conducting further research into the materiality of the skin as well as the introduction of functions as parameters in the evolutionary simulation. More specifically, the discussion herein highlighted the advancements made in the field of computational design and biomimicry used to improve the efficiency and functionality of the building shadings and skins. The goal here was to meet the ever-changing human needs while still providing a platform for efficiency and adaptability. This information was valuable in developing facade designs that seek to optimise energy performance while reducing the adverse impacts on the comfort of occupants.

The contribution of the research in the analysis and improvement of building skin design is highlighted below.

1. During phase one, a unique technique was produced to generate skin morphologies with phenotypic variants that can enhance the visual and thermal comfort level of the office floors of the selected buildings.

2. The second phase of the research experiment developed a workflow to fine-tune the outputted results of the generative process by making sure that the skin reaches the ultimate optimisation level by targeting users' most visited spots on each floor rather than any other spots of the building that occupants do not visit during working hours.

3. This research builds a bridge from the discipline of Architecture (outlined in Section 1.3.1) to Biology (biomimicry) (outlined in Section 2.1) to explore the possibility of applying morphological attributes throughout the evolution of skin systems (section 3.1). It also argues that data collection and lesson adaptation in architecture should not be limited to copying and inspiring from the forms of the organisms.

4. Furthermore, this study foregrounds the importance of building skin design exploration and their effect on resolving environmental issues such as extreme solar radiation. The investigation undertaken in section 4.1.4 covered this topic objectively and determined that biomimetic morphological configuration has a beneficial impact on prolonging the adaptive behaviours of skin tissues in comparison to their simpler mainstream building shading counterparts.

7 Appendix I: Applicability in Practice

This section provides details about further potential applicability of the workflow and analysis used in the design exploration method of this PhD study in practice that thrived from this research. In the figures below (figures 111, 112), the solar radiation and the view analysis developed for the experiments in section 4.1, were adopted in order to solve the conflicting problem of thermal and visual comfort as well as the space configurations. The figures below illustrate the results of the analysis of the multi-objective evolutionary plan and layout design that was adopted by Udex Architecture company (founded by the author) for a client based in South London. (Kaviani, 2020)

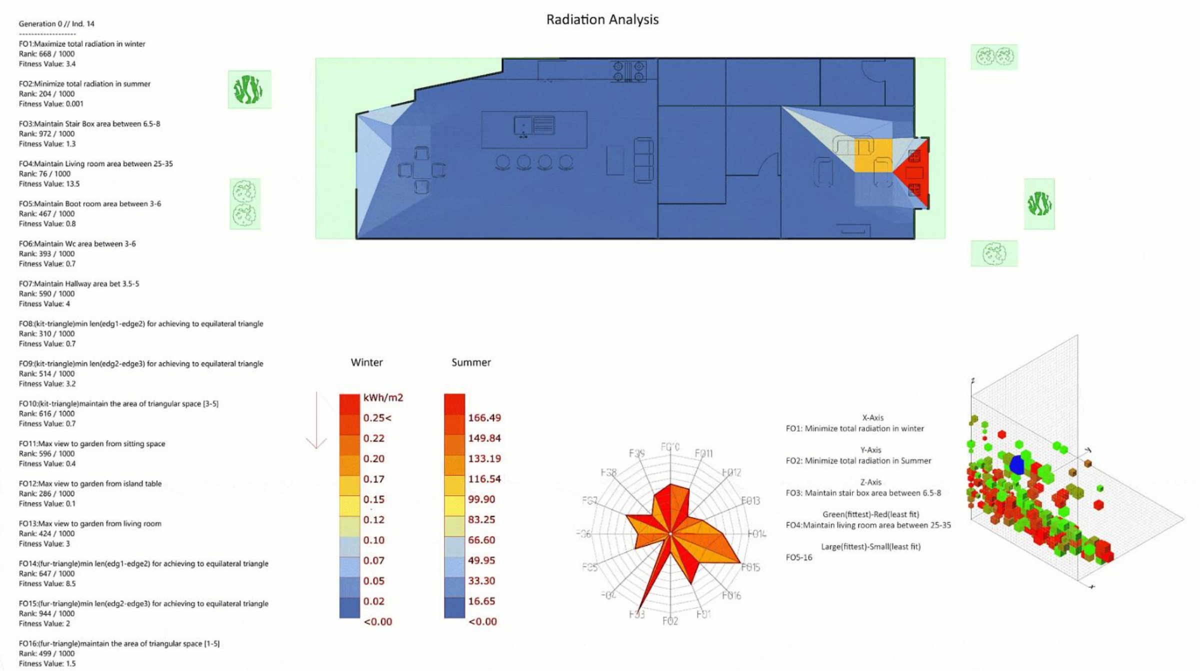

Figure 111 *Thermal analysis thrived from section 4.1.2.*

The project is a residential house called “White Block House” based in Bromley, South London. The ultimate goal in this project is three-fold: (1) to generate floor plans, i.e. optimise the generation of a large and highly diverse quantity of floor plan designs based on the client and council and the architect’s requirements, (2) to qualify floor plans, i.e. offer a proper classification methodology, and (3) to allow clients to “browse” through generated design options.

The analysis workflow and the computational platform that was used and performed in the White Block House project are extracted from the first phase of the simulation in section 4.1. White Block House is a fantastic practical example of where part of the outcome of using this research project has been used in practice.

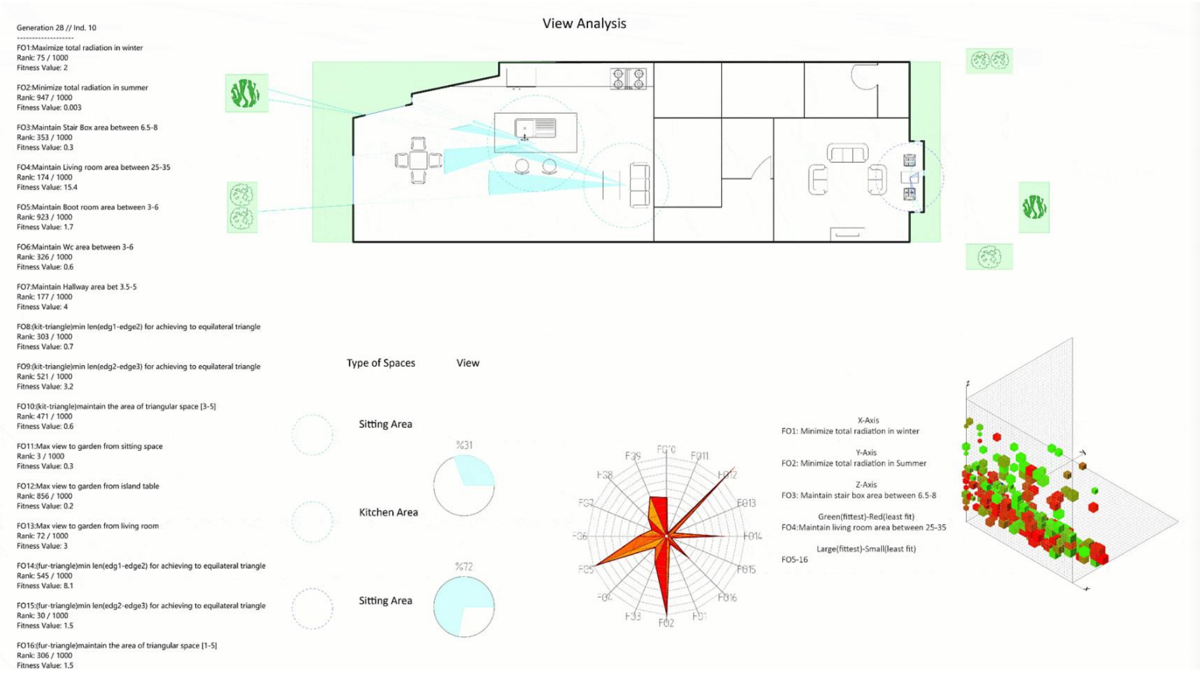

Figure 112 *View (visual comfort) analysis thrived from section 4.1.2*

For architects, starting off a project requires countless hours of research, both of understanding the design intent of the project and of projects in the past. This is where the evolutionary design methodology of this PhD research can contribute.

Figure 113 *Different conflicting Objectives implemented in the Evolutionary design process that thrived from the PhD study*

The requirement of the White Block project was to address all needs of clients as well as building regulations requirements while making sure that all our innovations and principles as architects are implemented in the design process in the shortest amount of time (figure 113). The multi-objective evolutionary workflow that was developed in this PhD study was used in the White House project in order to identify the design problem as computational objectives in the evolutionary algorithm and solve the view and thermal and space configuration problem of the project.

In the end, novel design solutions were discovered and navigated trade-offs between high-performing designs, sketch constraints, and goals led the architect to give the client the opportunity to browse between different design options that are illustrated with graphs data and confidently choose the most suitable one (Figure 114)

For further details and illustrations of the project, please refer https://udex.co.uk/white-blocks-house-plan-optimisation/

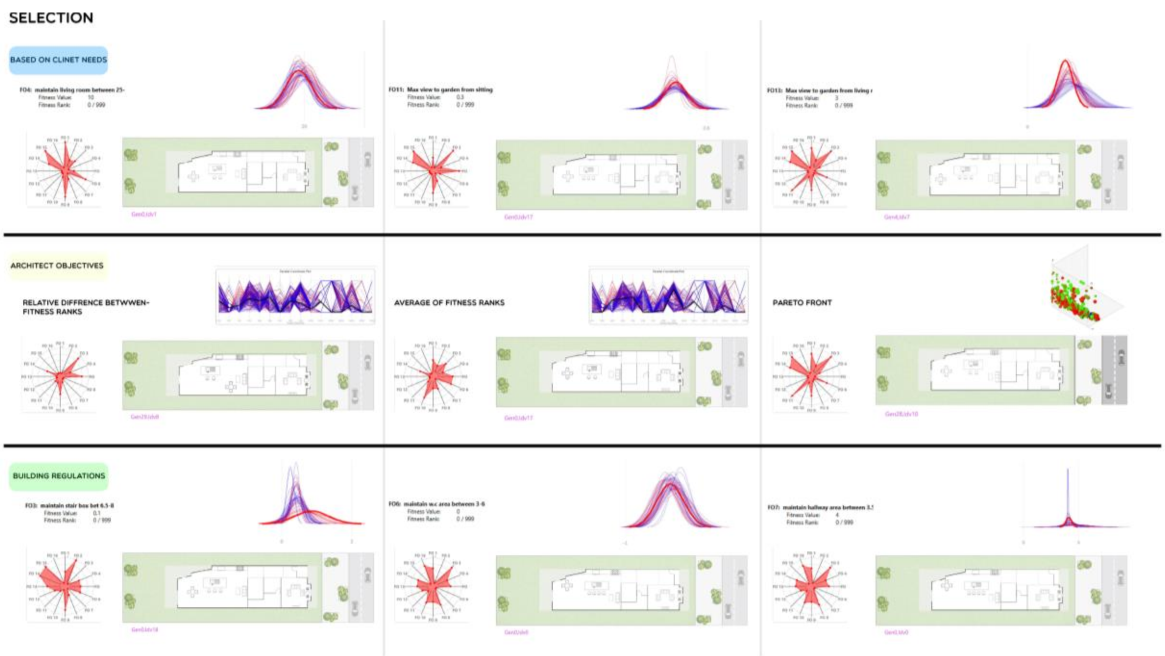

Figure 114 *Recommended and selected solutions from the EA-generated plans; presented with graphs so the client can browse and make an informed decision.*

8 Appendix II: Extended Drawings

This section comprises an extended set of drawings from the experiment setup of chapter 4. It provides further details about the way the view analysis during experiments conducted in this research.

The second drawing (figure 116) represents view vectors within the evolutionary design process getting detected as "blocked" when intersecting with the skin, resulting in the identification of view performance percentages.

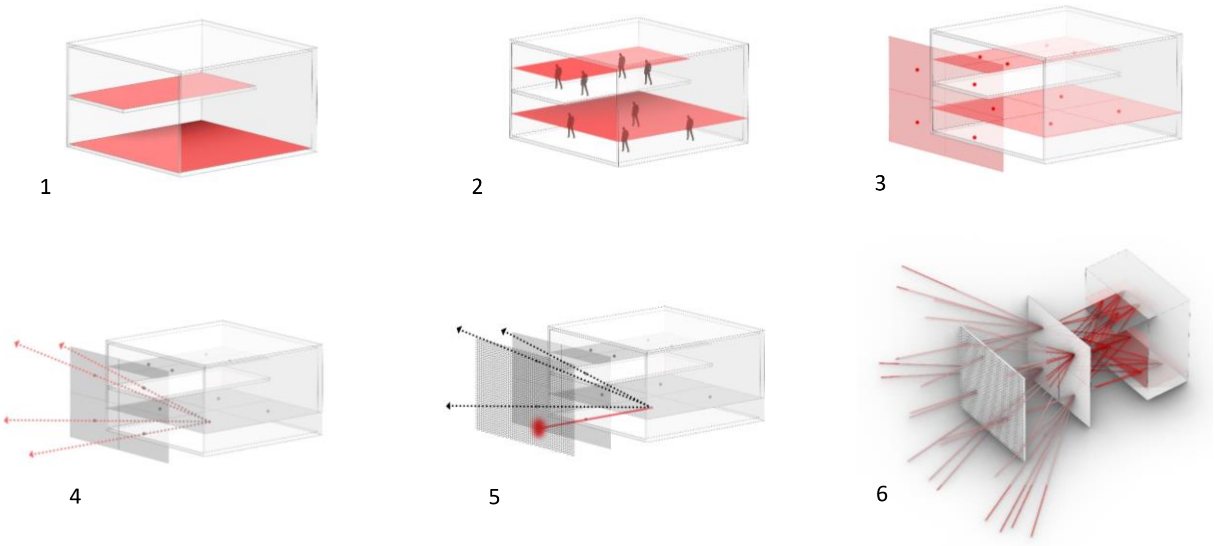

Figure 115 *View Analysis procedure with more details*

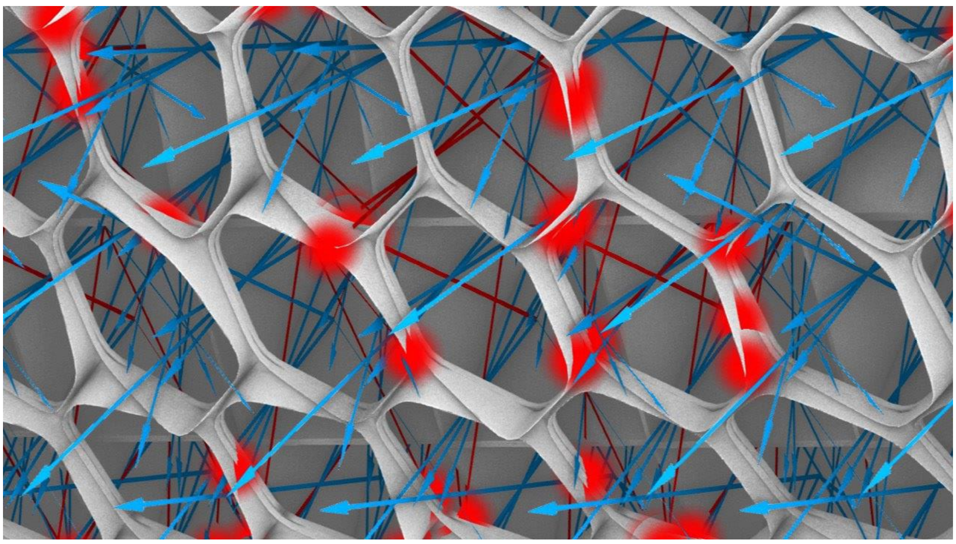

Figure 116 *The Illustration of in way view vectors can detected "blocked" when intersect the skin*

9 Glossary [23]

Term	Definition
Adaptive Thermal Comfort	*The comfort model that is the result of an extensive field study on the occupants comforts level. It is based on the notion that people dynamically interact and adapt to their environment by different means such as clothing and activity preferences.*
Crossover	*The exchange of genes between two solutions / individuals (computation).*
Crossover Distribution Index	*This index is between 0 -100. A large distribution index value gives a higher probability for creating offspring near parent solutions and a small distribution index value allows distant solutions to be selected as children solutions (computation).*
Crossover Probability	*This value is between 0.0 to 1.0. The percentage of solutions in the generation that will reproduce for the next generation (computation).*
Design Problem	*The algorithmic method by which the design is expressed through 'fitness objectives', and 'genes' and their expression in the construction of the 'phenotype.'*
Divergence	*When the fitness values of solutions evolved by an evolutionary simulation are distant from one another (thus increasing variation).*
Evo-Devo	*Abbreviation of Evolutionary Development - A subfield of evolutionary biology that examines the role of developmental biology in the evolutionary process.*
Evolutionary Model	*The computational setup of a design problem to be solved with the application of evolutionary computation. It comprises the calculation of the fitness objectives, rules and regulations in the genome of the experiment and their expression in the phenotype.*
Evolved City	*A city that has developed through a process of self-organisation and emergence throughout its history, leading to complex systems that are informed by environmental conditions.*
Extrinsic	*External*
Fitness Criteria / Fitness Objective	*The design objectives and the goals that the evolutionary simulation will optimise for, and based on which the generated phenotypes will be evaluated*
Fitness Function	*The mathematical functions that calculate the fitness objectives values in the design problem.*
Fitness Graph Chart	*The fitness Chart (sometimes referred to as the 'star coordinate method' or 'diamond chart') analyses the fitness values of a single solution (as opposed to the population wide analysis). The aim is for the user to better understand how a single solution performs by comparing the fitness values and ranking for each of its fitness objectives.*
Fitness Landscape	*The distribution of solutions of the search space in relation to one another and the relative complexity of the evolutionary simulation from navigating the solutions towards finding the fittest solution set (global optima).*
Fitness Rank	*The ranking of each solution within the population according to its fitness value.*
Fitness Value	*The empirical performance measure attributed to each generated solution/phenotype according to its evaluation results in the simulation.*
Gene	*A single variable that defines one part of an individual. In Grasshopper3D, this variable is represented by a numeric slider (computation).*
Gene Group	*A group of genes in the genotype of the experiment that performs a similar task (computation).*

[23] Some of the technical definitions in this section are extracted from the Wallacei Primer (Makki, M., Showkatbakhsh, M, 2019)

Generation	*A single iteration of the evolutionary algorithm (computation).*
Generation Count	*Number of generations (iterations) to be run by the evolutionary simulation (computation).*
Generation Size	*Number of generated solutions/phenotypes within each generation (computation).*
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.*
Homeostasis	*The biological process that keeps the steady-state of the organisms in both individual or collective scales in the face of internal or external perturbations.*
Homeostatic Behaviour	*The behaviour of an organism that leads to homeostasis.*
Homeostatic Process	*The biological process of reaching homeostasis in species that comprises the coordinate actions of sub-systems within individual species or the members of a colony on a collective scale.*
Individual / Solution	*A unit that is generated by the evolutionary simulation. It is represented by a genotype and phenotype. The population comprises of the individuals.*
Intrinsic	*Internal*
Mean Radiant Temperature	*Considering only the radiant heat transfer in the temperature calculation. The amount of radiant heat that is transferred to the object.*
Mean Value Trend Line Graph	*The mean fitness values trendline graph calculates the mean fitness value for each generation in the population generated by the evolutionary simulation and displays each value as a point from left (first generation) to right (last generation).*
Modern Synthesis	*The acceptance of 5 key Darwinian principles by the majority of evolutionary scientists in the 1940s.*
Morphogenesis	*The biological process by which a cell, tissue, or organism takes on its shape is known as morphogenesis. Along with the regulation of tissue growth and the patterning of cellular differentiation, it is one of the three fundamental elements of developmental biology.*
Morphological Intervention	*The localised and bottom-up formal and geometrical processes that are applied to the phenotypes in the evolutionary simulations.*
Multi-Objective Optimisation	*An optimisation simulation comprises of multiple fitness objectives to be optimised independently from one another.*
Mutation	*A change in a gene (or group of genes) in a genotype (computation)*
Mutation Distribution Index	*This index is between 0 - 100. A large distribution index value gives a higher probability for creating offspring near parent solutions and a small distribution index value allows distant solutions to be selected as children solutions (computation)*
Mutation Probability	*The probability of a gene to mutate. This determines how many genes in a solutions genotype will mutate (computation).*
Natural Selection	*Organisms that are selected for survival according to their fitness to environmental conditions.*
Objective Space	*The distribution of solutions selected by the evolutionary algorithm in relation to their fitness values in a 3d coordinate system.*
Ontogenetic	*The developmental history of an organism within its own lifetime.*
Operative Temperature	*Considering the radiant heat transfer and convection heat transfer in the temperature calculation. Operative temperature is described as effective temperature since it has the combined effects of radiation and convection heat transfers.*
Optimisation	*The increase in fitness of a solution or population towards a very fit (or at times the fittest) value. The fit value in the context of WallaceiX (utilised plugin to run evolutionary simulations in the research) refers to the minimum value.*
Optimisation Trend	*The trend of the optimisation from the beginning of the simulation to the end.*

Pareto Front	*The solutions that are non-dominated by another solution. i.e. a solution that cannot be improved without negatively affecting the rank of another solution.*
Phylogenetic	*The evolutionary development and diversification of species.*
Phenotype	*The morphological (or otherwise) representation of the solution. The phenotype is the manifestation of the genotype*
Parallel Coordinate Plot Graph	*The parallel coordinate plot (PCP) analyses all the solutions in the population by comparing the fitness values for each solution across all fitness objectives. In the PCP, each fitness objective is attributed a y-axis, in which the first objective is the left most y-axis, and the last objective is the right most y-axis. The solutions are coloured from red (solutions in the first generations) to blue (solutions in the last generation).*
Population	*All individuals generated by the evolutionary simulation across all generations (computation).*
Populationist	*Highlights the uniqueness between solutions within a given population.*
Primitive	*The constructed phenotype of an evolutionary simulation prior to the simulation run.*
Radiation	*The emission of electromagnetic heat waves from a warmer object to an object with a cooler surface*
Random Seed	*Random seed in the evolutionary simulation that can be controlled from within the Wallacei X UI.*
Regulation (Genes)	*The control of which genes act on which body parts*
Search Space	*All the possible solutions that can be explored by the evolutionary algorithm.*
Social Regulation	*Highlights the uniqueness between solutions within a given population*
Simulation	*A single algorithmic run of the evolutionary solver (WallaceiX in this research) from start to finish.*
Standard Deviation Graphs	*The Graphs that show the distribution of a set of values from the mean value per generation in the evolutionary simulation. The Standard Deviation (SD) graph calculates the SD for each generation in the population and plots each generation to 3 SD values on either side of the mean. The generations are coloured from red (first generation) to blue (last generation)*
SD Trend line Graphs	*The standard deviation (SD) trendline graph calculates the SD value for each generation in the population and displays each value as a point from left (first generation) to right (last generation).*
Thermal Behaviour	*The thermal behaviour of a building refers to the processes of heat and energy exchange between external and internal environments through the building itself.*
Thermal Comfort	*Thermal comfort is assessed by the subjective evaluation (solar radiation analysis proposed in this study) and refers to the satisfaction of a person in an environment.*
Thermal Zone	*Similar to the biological organisms, buildings have a metabolism. They can be considered as thermal systems, with a series of heat inputs and outputs. A thermal zone refers to a space or a collection of spaces that have similar space-conditioning requirements such as heating and cooling requirements.*
Thermoregulation	*Highlights the uniqueness between solutions within a given population.*
Typologist	*Considers the average solution of a population as an adequate representative of all solutions in the population.*
voxelisation	*Voxelisation is the process of converting a data structures that store geometric information in a continuous domain (such as a 3D triangular mesh) into a rasterised image (a discrete grid).*
Visual Comfort	*Visual comfort is assessed by the subjective evaluation (the unique users view analysis proposed in this study) and refers to the satisfaction of users in a room in terms of having a good view field to the outside of the building.*

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