Revolutionizing Architecture: Integrating Nanotechnology and Dielectric Materials for Advanced Hemostatic Façade Systems

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Abstract – *This paper discusses the potential of emergent materials in architecture to address critical issues in our built and natural environment, particularly in relation to the climate crisis exacerbated by contemporary behaviors and architecture. With more than half of the world's population living in cities, the problem is complex and requires interdisciplinary attention to various scales from urban to Nano. Nanotechnology offers opportunities for adaptation and innovation, enabling us to understand and manipulate the materiality of our surroundings. The paper advocates for the inclusion of architecture and design in interdisciplinary research endeavors focused on nanotechnology to promote innovation in sustainability. In architectural practice, nanotechnology has useful applications in high efficiency coatings and claddings, although this approach is additive rather than integrative in transforming energy production and consumption. The paper also discusses recent material advancements and considers their potential for architectural design.*

Keywords: *nanotechnology, parametric design, energy, materials, kinetic facade, thermal performance.*

I. Introduction

A self-regulating façade system developed by a New York-based firm Decker Yeadon controls the building's climate by automatically responding to the environmental condition. The maze-like façade is made up of dielectric material which is coated with silver electrodes. Scientists have developed the ability to manipulate materials at a molecular and atomic level, allowing for the creation of structures at a tiny scale [1]. One method for fabricating these nanometer-sized structures is through self-assembly, which mimics the process by which cells in living organisms assemble atoms to create essential building blocks. Researchers have replicated this process in laboratories to create building blocks for advanced materials, building from the bottom up. A group of researchers at Harvard University have successfully fabricated complex synthetic molecular structures and devices using DNA, which resemble the building blocks of the popular LEGO toy. These DNA bricks and the toy building blocks share two key similarities: they consist of a finite number of discrete elements and can be assembled into a wide range of shapes[2].

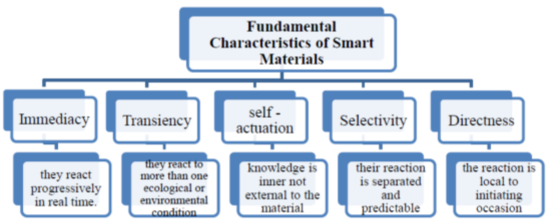
While the toy bricks are manufactured using injection molding, the DNA bricks are assembled atom by atom in a bottom-up process through rapid prototyping. Once the bricks are formed, larger structures are created via self-assembly. This approach offers scientists and materials engineers the opportunity to create material structures with precise geometries, specific surface structures, and varying porosities[2].

They can also introduce guest molecules to refine the material structures, imbuing them with more properties or even turning them into functional molecular devices

II. THE NEXT GENERAL-PURPOSE TECHNOLOGY

The system operates by responding to changes in the surrounding environment, such as changes in temperature or sunlight, and adjusting the amount of light and heat that enters the building accordingly[3].

Fundamental characteristics of Smart Materials. Source: researcher based on (Addington, 2005).



The silver electrodes on the surface of the dielectric material allow for the electrical charge to be distributed across the façade, creating a network of sensors that can detect changes in the environment. When the temperature rises, for example, the electrical charge within the façade changes, causing it to darken and reduce the amount of sunlight that enters the building. Conversely, when the temperature drops, the façade becomes lighter, allowing more sunlight to enter and warm the building[4].

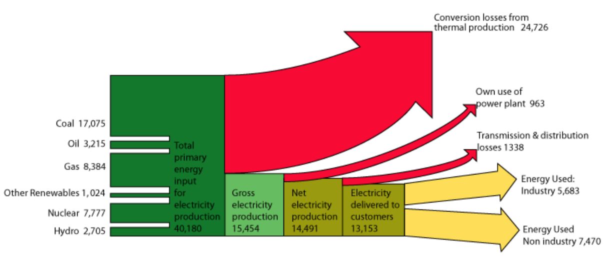


Figure 1: US Electricity Flow 2011 | Supply and Use in Trillion
Source: https://www.resilience.org/stories/2016-04-18/an-energy-diet-for-a-healthy-planet-part-ii/

II.1. ADAPTINGDIELECTRIC MATERIALS

The focus of current laboratory research on emergent materials is not necessarily on their potential architectural applications. Before we can utilize these new substances in architecture, we need to fully understand their capabilities and explore their possible uses. Polymorphic materials, a type of smart material that can alter their size or shape in response to environmental changes, are particularly promising for architectural applications.

One example of a polymorphic material with potential architectural uses is Electro Active Polymers (EAPs), also known as "artificial muscles". EAPs consist of a polymeric membrane placed between two electrodes. When a high voltage is applied to the system, the electrostatic forces between the electrodes cause the membrane to expand or contract[5].

In laboratories, researchers are exploring emergent materials that may not have been initially developed for architectural purposes. However, to fully understand their potential for use in architecture, it is necessary to evaluate their complete capabilities and identify potential applications in this field. One group of materials that exhibit promising adaptability for architectural needs are polymorphic, which can alter their size or shape in response to changes in their environment.

An example of such polymorphic materials is Electro Active Polymers (EAPs), which are also known as "artificial muscles". EAPs consist of a polymeric membrane that is positioned between two electrodes. When a high voltage is applied to the system, the electrostatic forces between the two electrodes cause the polymer to deform. These new materials are being studied for various purposes, including as soft muscles in robotics, micro-electromechanical systems, fluidic pumps, and even for creating soft airships such as blimps[5].

Electro Active Polymers have gained interest in architecture mainly for their ability to regulate daylight in building facades. Decker Yeadon LLC has developed the Homeostatic Façade System which utilizes these artificial muscles to regulate the amount of solar heat gain in a screen system by controlling the openings. The EAP is wrapped around a flexible core that can bend in response to the expansion or contraction of the actuator.

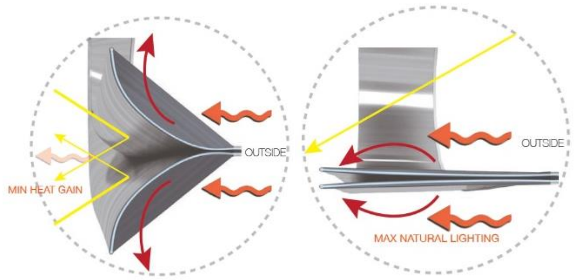
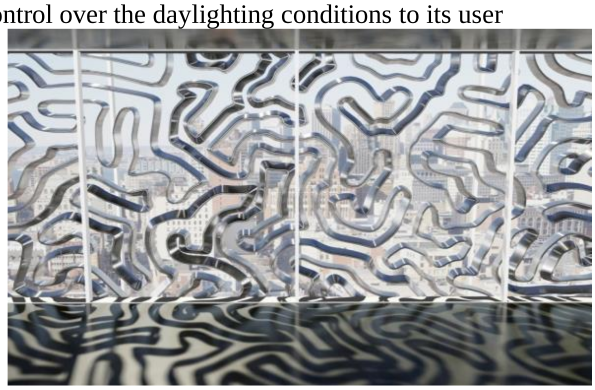


Figure 2: Actuator Assembly Homeostatic Façade System by hanzhaoh@uoregon.edu
Source: https://www.archdaily.com/101578/moving-homeostatic-facade-preventing-solar-heat-gain

II.2. Electroactive Polymers (EAPs)

façade system, this use of EAPs opens up the possibility of an adaptive Parametric façade that can respond to changing external conditions such as solar radiation, thermal performance, or wind. The flexibility of the EAP material allows for a dynamic response as kinetic movement that can be fine-tuned to achieve the desired performance. Additionally, the ease of installation and low energy consumption make EAPs an attractive option for sustainable building design. The lightweight nature of the assembly enables a straightforward adhesive installation within double glazed facades. However, the functionality of the screen goes beyond simply substituting a mechanical actuator in a shading system, as the materials assembly itself is essential to its performance. By using the highly reflective silver electrodes that cover the polymer core, the facade system can reflect daylight to redirect it either inside or outside of our interior spaces. As the materials assembly can be activated at any point during the design process, the system provides a high level of control over the daylighting conditions to its user



. Figure 3: Homeostatic Façade System by Kelly Minner proposed in double skin façade system
Source: https://www.archdaily.com/101578/moving-homeostatic-facade-preventing-solar-heat-gain

Continuous research is focused on enhancing the capabilities of EAPs. The lifespan and effectiveness of EAPs' polymorphic transformation are largely dependent on the adjacent laminar electrodes, which need to be both flexible and highly elastic while retaining their conductivity during any formal transformation. To achieve these parameters, two main methods are used to create the essential electrode structures: using thin metal electrodes or carbon-based material.

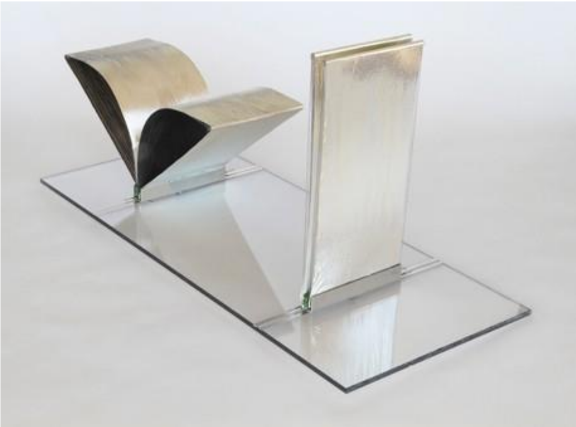


Figure 4: Homeostatic Façade System mockup by Kelly Minner
Source: https://www.archdaily.com/101578/moving-homeostatic-facade-preventing-solar-heat-gain

To achieve conductivity, the Homeostatic Façade System employs a thin layer of silver electrodes that are only 200 nm thick, which exhibit excellent conducting properties. These electrodes are applied onto the corrugated core polymer surface of the EAP, conforming to the substrate's surface geometry and performing only within specific parameters. However, if the polymer is stretched beyond the allowed limit,

the electrodes will fail beyond repair. Additionally, due to the electrodes' extreme thinness, they may be prone to corrosion over time.

A material commonly used as an alternative to metal electrodes for EAPs is carbon-based particles at the nano-scale, which have shown promise. These particles are bonded to the core polymer and can be applied in various ways. For instance, they can be suspended in a viscous oil called carbon grease, which can be spread onto the surface. Another option is conductive rubber, where the carbon particles are dispersed in an elastomer that is cross-linked after it has been applied to the EAP core. Alternatively, carbon particles can be applied directly to specific elastomer cores if they possess adhesive properties[6].

Shape Shift is a research project that explores the architectural applications of EAPs with carbon-based electrodes. The project was a collaboration between the Chair of Computer Aided Architectural Design at ETH Zürich and the Swiss Federal Laboratories for Materials Science and Technology (EMPA), involving students, professionals, and educators from various fields such as architecture, art, design, biophysics, programming, and environmental design. The project aimed to create a dynamic shading system that can also control airflow, but it also explored the potential of using the lightness of the materials assembly to develop dynamic structural elements for the built environment. The team envisioned a responsively transforming and shape-shifting architecture[6].

II.3. Biomimicry Inspiration

The main inspiration for Yeadon’s façade techniqueis muscles, and homeostasis in biological system.The similarity is between the actuator that operatesto activate the system in similar with how musclesact Fig. 5. Temperature is an example for the. internal conditions regulated by homeostasis organisms. Yeadon’s façade controls the building temperature by responding to external environmental changes and conditions. By doing so, they are aware of the local environmental conditions resulting in the usage of locally material and available power.

Figure 5 Project insects architects
Source: https://en.idei.club/49789-biomimicry-architecture.html

II.4. Shape-Shift Project

EAP with carbon-based electrodes for façade applications

Shape shift is considered to be a trial in the materialization of architecture. This research discovers the possible uses of electro-active polymer (EAP) at a scale of architecture and how to maximize the benefit from the EAP[5].

Fig. 6 muscles movement.
Source: https://youtu.be/4XGVMXCxBNA

provides a novel interconnection to space built throughout its distinctive potentials properties. It is characterized by an ultra- light weight, elastic material with the capability of changing form deprived of the necessity of motorized actuators[6].

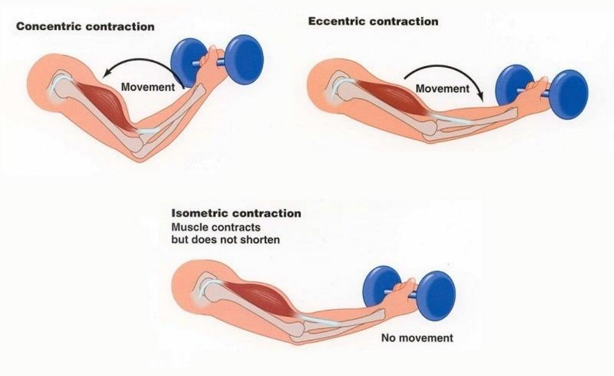


Fig. 7 muscles movement.
Source: https://mungfali.com/#h

Dielectric elastomers which are special electroactive polymers are used in this project to test the creation of dynamic spatial applications.
Dielectric elastomers are considered to be polymer-based actuators that varies in their dimensions in term of shapes, size and volumes directly when exposed to a massive electrical field. These elastomers have a high level of deformation which in terms make them fine, translucent, lightweight and come out from the active materials filed.

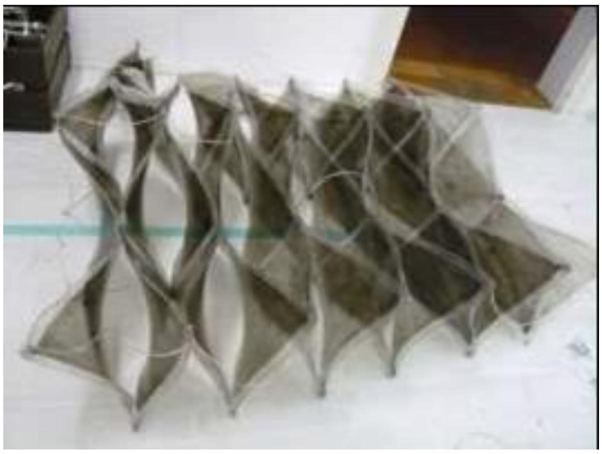


Fig. 8 muscles movement.
Source: https://link.springer.com/chapter/10.1007/978-3-319-76889-2_8

Illustrating a new proposal of smart skin that could be used as a great alternative for any new or existing buildings' facades by applying some features and techniques of merging smart materials with advanced parametric geometries. The approach of reaching the skin will be based on creating a pattern inspired from surrounding nature which consists of smart geometry objects that has the feature to act consistently and Instantaneous without human interference.

Using of variable levels of Smart Materials imbedded in an advanced parametrized shape to create an inspirational pattern that could be used as a new proposal of façade design and screening to create new method of reaching a sustainable stunning environment inside and surround architectural buildings within the city.

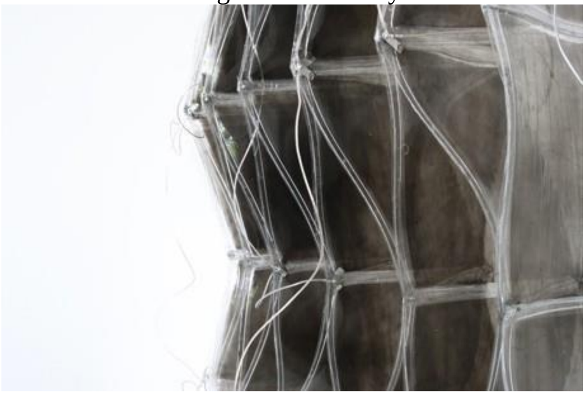


Figure 9: ShapeShift | EAP with carbon based electrodes for façade applications | Image by Manuel Kretzer
Source: https://link.springer.com/chapter/10.1007/978-3-319-76889-2_8

III. Solar Technologies

Photovoltaic technologies are another category of materials that can benefit from nanoscale optimization and calibration. Researchers are currently designing various improvements to material structures to make them suitable for Building Integrated Photovoltaic (BIPV) Systems. This approach aims to reduce the manufacturing costs of photovoltaic systems during the construction process and offset these costs by achieving savings over a certain period of operation[7].

To optimize photovoltaic technologies for Building Integrated Photovoltaic (BIPV) Systems, many material structures are being designed with nanoscale optimization and calibration. One such technology is the multijunction solar cell, which can achieve 44% efficiency by stacking various components tuned to harvest specific wavelengths of light. However, despite their impressive performance, the current high production costs of these cells present a challenge for large-scale installations in architectural settings.

The Integrated Concentrating Dynamic Solar Façade (ICSF) is an example of a facade installation that has successfully integrated multifunction solar cells in an economically viable manner. This modular system employs Fresnel lenses to actively track the sun and concentrate sunlight onto a gallium arsenide concentrator array produced by Spectrolab [7].

The Center for Architecture Science and Ecology (CASE), a collaboration between Rensselaer Polytechnic Institute and Skidmore, Owings & Merrill LLP, developed a strategy to fully utilize the high-performance solar cells that were initially designed for aerospace applications, in the construction of Building Integrated Photovoltaic

(BIPV) systems [8].. The Integrated Concentrating Dynamic Solar Façade (ICSF) is an example of BIPV that has been installed at the Center of Excellence at the University of Syracuse. It is a multifunctional building element that not only generates electricity but also provides thermal energy and regulates day-lighting while controlling solar heat-gain[7].

To optimize photovoltaic materials for BIPV applications, researchers are focusing on guiding photons on a smaller scale within the materials themselves. Nanotechnology is being used to enhance Dye-Sensitized Solar Cells (DSSCs) by incorporating photonic crystals with distinct nanostructures that strongly interact with light.

The design of the photonic crystals can be tailored to scatter or direct specific wavelengths of light. While DSSCs are structured and manufactured at the macro scale, their high surface structure of titanium dioxide (20nm) nano-crystals coated with dye molecules contributes to their efficiency. By adding photonic crystal back-reflection layers to the material assembly, previously unabsorbed photons can be guided back to the dye molecules, leading to increased light absorption and efficiency without sacrificing visible transparency. This approach is being pursued by physicists and chemists working on the nanoscale [9].

IV. Thermo-Bimetal Manipulation Project: Taming Thermo-Bimetal To Behave.

Thermo-Bimetal is known as type of smart material that twists and turns to cruel when it is exposed to heat, also it can give mechanically movement of its' surface for serving the building shadow, ventilation, self-assemble, reinforcement, and shape transformation. Also changing the character of molecular of the coated metal, its performance can be enhanced, improved, and also even annulled dependent on the shape. thermos bimetal began to be used, two metals sheets plating together with a variation in the thermal expansion coefficients for each one of them, so the material is exposed to heat or cold it deforms. And when the temperature increases, the expansion happens in a side of the laminated sheet greatly than the other side and that creates a curl within the sheet as an outcome from this composite[10].

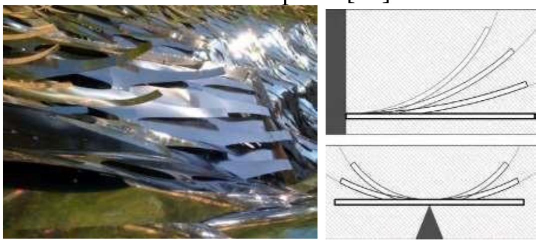


Fig. 10 Curled thermos-bimetal surface.
Source: https://www.archdaily.com/215280/bloom-dosu-studio-architecture

The production of DSSCs is cost-effective due to their ability to be printed or coated in a simple process, making them a cheaper alternative to first-generation silicon solar cells. While they may not be as operationally efficient, their wide absorption angle and flexibility make them versatile in their installation [11].

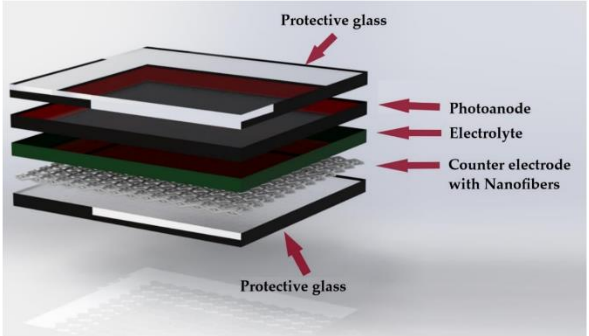


Figure 11: Design of a DSSC | the TiO2–SiO2 nanoparticle multilayer is functioning as a highly reflecting photonic crystal
Source: https://www.mdpi.com/1996-1944/12/19/3190/xml

An example of this is The Light Sanctuary, a proposed landscape installation by Decker Yeadon LLC in the United Arab Emirates. The installation features a 50km-long and 10-30m-wide solar ribbon that can be vertically looped and is designed to vibrate sand and dust particles off of its flexible surface, making it somewhat self-cleaning[12].

Figure 12: Light Sanctuary by Decker Yeadon LLC
Source: https://www.designindaba.com/articles/creative-work/mirage-solar-power

DSSCs have the advantage of being visibly transparent, which means they can be used for both solar energy collection and daylight control in building exteriors. They can also be manufactured in a range of colors. To make DSSCs more suitable for BIPV applications, researchers from Finland and Spain collaborated with solar industry partners from Sweden to develop tools for designing and optimizing these solar technologies[13]. By combining experimental and computational approaches, the team created a method that allows them to predict the color and transparency of DSSCs based on their photovoltaic efficiency. This could be an invaluable tool for manufacturers looking to respond to the increasing demand for creative architectural applications of BIPVs.

V. INTERDISCIPLINARY APPROACHES IN ARCHITECTURE

Polymorphic smart materials have the potential to improve the performance of building systems and aid in energy conservation, while DSSCs can generate electricity from sunlight. These materials demonstrate the potential of emergent materials and the importance of interdisciplinary collaboration between researchers in

STEM fields, architecture, and design in advancing these technologies for building applications. These two examples showcase how advancements in these materials have been achieved through the collaboration of experts from diverse disciplines.

To tackle the complex problem of energy consumption in the built environment, a multidisciplinary approach is necessary. Nanotechnology offers a range of possibilities for sustainable architecture and requires expertise from various fields, making it inherently interdisciplinary. Interdisciplinary research (IDR) lies at the core of nanomaterials research and design, involving the fusion of information, data, tools, techniques, perspectives, concepts, and theories [12].

This approach has implications for innovative social organizations and collaborations in design practice, as well as cross-programmatic and interdisciplinary formats in pedagogy and teaching. To participate in interdisciplinary endeavors, designers and architects must learn to communicate effectively across disciplines and be willing to learn new methods, languages, tools, and cultures, necessitating new attitudes towards research, theory, and practice [13].

VI. Proposal of shading device of Cairo university façade:

This paper presents a detailed proposal for the implementation of a homeostatic façade, specifically designed for the Faculty of Engineering at Cairo University. The proposed shading device aims to enhance energy efficiency, improve occupant comfort, and provide an aesthetically pleasing and sustainable solution. This paper provides an overview of the concept, design considerations, and potential benefits of integrating a homeostatic façade into the existing building structure. Detailed illustrations are also provided to visualize the proposed design.

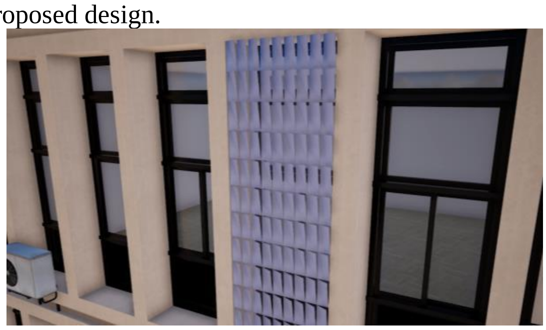


Figure 13: Cairo University Façade by Author
Source: https://youtu.be/3uZUH7pi77g

comprehensive performance analysis of shading devices implemented in building façades to enhance energy efficiency and occupant comfort. The study focuses on thermal analysis, daylighting simulation, energy performance evaluation, and occupant comfort analysis. Various shading devices, including homeostatic façades, are examined to understand their effectiveness in mitigating solar heat gain and optimizing natural lighting while maintaining occupants' thermal comfort. The analysis is carried out using computer simulations and validated against real-world case studies. The results provide valuable insights for designers, architects, and building professionals seeking to improve building performance through shading devices.

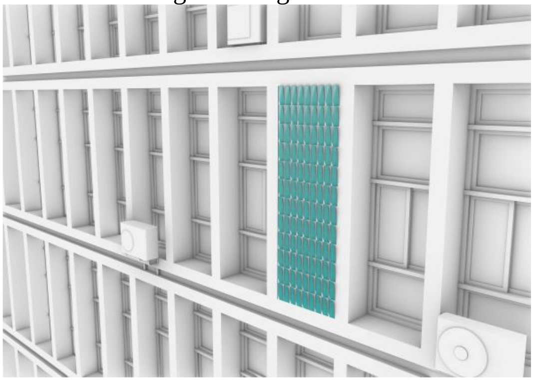


Figure 14: Cairo University Façade by Author
Source: https://youtu.be/3uZUH7pi77g

This article provides in-depth insights into the simulation and performance analysis of shading devices, specifically focusing on thermal analysis, daylighting simulation, energy performance evaluation, and occupant comfort analysis. The findings and discussions presented in the article contribute to the understanding of how shading devices can effectively improve building performance and occupant well-being.

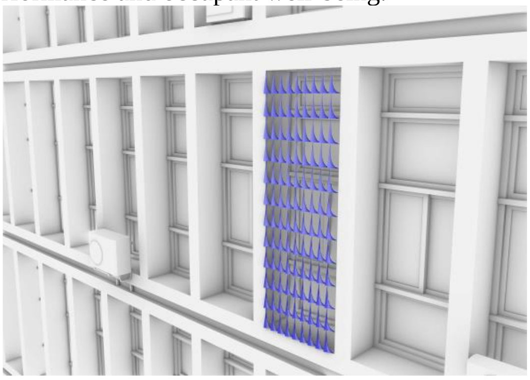


Figure 15: Cairo University Façade by Author
Source: https://youtu.be/3uZUH7pi77g

Overview of the Proposed Shading Device:

This section provides a comprehensive overview of the proposed shading device for the Faculty of Engineering, Cairo University. It describes the design concept, emphasizing the key features and functions of the shading device. The analysis includes an explanation of how the shading device integrates with the existing façade and its overall impact on the building's aesthetics and energy performance.

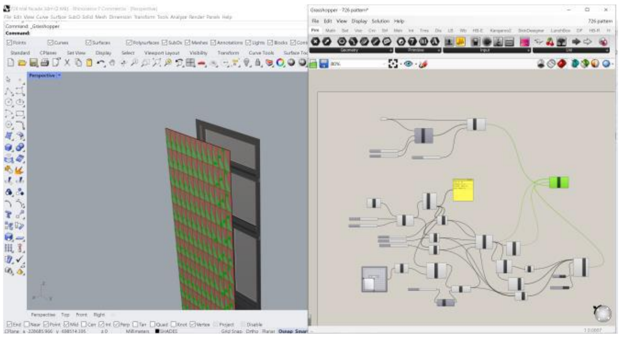


Figure 16: Script for facade Façade by Author
Source: https://youtu.be/3uZUH7pi77g

Script used to perform the idea

In this section, the external façade configuration of the proposed shading device is discussed in detail. It covers aspects such as the design of the shading elements, their arrangement, and the overall architectural integration with the building. The analysis explores various configurations and their effects on solar heat gain, daylighting, and visual comfort.

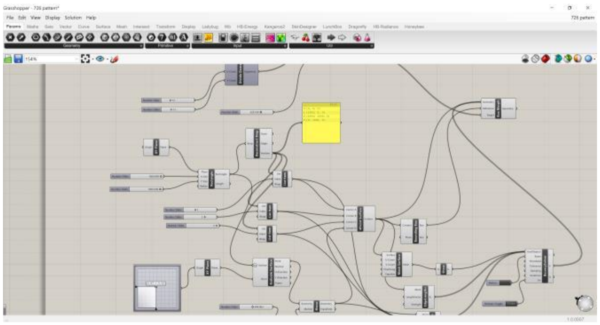


Figure 17: Script for facade Façade by Author
Source: https://youtu.be/3uZUH7pi77g

The shading control mechanism is a crucial aspect of the proposed design. This section delves into the details of how the shading device is controlled and regulated. It discusses the use of sensors, actuators, and automation systems to optimize the shading device's performance in response to changing environmental conditions, such as solar intensity, wind speed, and occupant preferences.

Adaptive Façade Elements:

The concept of adaptability is highlighted in this section, focusing on the façade elements that can dynamically respond to external factors. The analysis explores the use of smart materials, such as electrochromic glass or phase-change materials, to achieve adaptive shading and thermal insulation. It also discusses the integration of advanced technologies, such as machine learning algorithms, to optimize the adaptive behavior of the façade elements.

Energy Harvesting and Storage:

Energy harvesting and storage mechanisms are crucial for the proposed shading device's sustainability and self-sufficiency. This section discusses different methods of energy harvesting, such as photovoltaic cells integrated into the shading elements or kinetic energy recovery from wind or occupant movement. It also explores energy storage solutions, such as batteries or thermal storage systems, to ensure energy availability when needed.

Thermal Analysis:

Thermal analysis focuses on assessing the proposed shading device's impact on the building's thermal performance. This section includes computer simulations and modeling techniques to analyze heat transfer, solar heat gain, and thermal comfort. The analysis compares different scenarios, considering factors such as different shading configurations and materials, to determine the most effective thermal performance.

Daylighting Simulation:

Daylighting simulation evaluates the proposed shading device's impact on the building's natural lighting conditions. This section uses advanced daylighting software to assess parameters such as daylight levels, distribution, and glare control. It compares different shading configurations to optimize daylighting performance while minimizing energy consumption for artificial lighting.

Energy Performance Evaluation:

Energy performance evaluation focuses on quantifying the proposed shading device's impact on overall building energy consumption. This section utilizes building energy simulation software to assess energy savings achieved through reduced cooling loads, lighting energy reduction, and the integration of energy-efficient technologies within the shading device.

Occupant Comfort Analysis:

Occupant comfort analysis assesses the proposed shading device's influence on indoor thermal comfort, visual comfort, and overall occupant satisfaction. This section utilizes comfort metrics, subjective surveys, and thermal comfort models to evaluate the device's effectiveness in providing a comfortable and productive indoor environment for building occupants.

By conducting a thorough analysis of each of these sections, the paper provides a comprehensive understanding of the proposed shading device's design, its impact on thermal performance, daylighting, energy consumption, and occupant comfort. The findings from the analysis guide the design process and provide valuable insights for achieving an optimized and sustainable shading solution for the Faculty of Engineering at Cairo University

VII. Conclusion

The article discusses various advancements in material science and nanotechnology and their applications in architecture. The focus is on two main areas: electroactive polymers (EAPs) and photovoltaic materials. EAPs are being developed with highly conductive, flexible, and elastic adjacent laminar electrodes to enhance their capabilities. Two methods are commonly used to create the essential electrode structures: thin metal electrodes or carbon-based particles at the nano-scale. Shape Shift is a research project that explores the architectural applications of EAPs with carbon-based electrodes, envisioning a dynamic, shape-shifting architecture. In photovoltaic materials, researchers are focusing on nanoscale optimization and calibration to make them suitable for Building Integrated Photovoltaic (BIPV) Systems. Dye-Sensitized Solar Cells (DSSCs) are being enhanced by incorporating photonic crystals with distinct nanostructures that strongly interact with light, leading to increased light absorption and efficiency. Nanotechnology is also being used to tailor the design of photonic crystals to scatter or direct specific wavelengths of light.

Acknowledgements

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She has extensive experience in academia, serving as a Demonstrator, Teaching Assistant, Assistance Professor, and now as an Associate Professor at October 6 University. Henar has a diverse range of research interests, focusing on General Environmental Design and Control, with a specialization in Sustainable Design and Environmental Control. Her previous publications span various topics related to her research interests.

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