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Design of Innovative Parametric/Dynamic Façade Integrated in the Library Extension Building on UAEU Campus †

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Abstract: The building industry is in constant change and the United Arab Emirates (UAE) is a leader in innovative solutions for green buildings. The standards used in achieving sustainable buildings, such as LEED, Estidama, have contributed to building structures that reduce energy consumption. More than 40% of the total energy is consumed by residential and commercial buildings as electricity. The strategies applied in a building in order to have low energy consumption vary depending on the region and climate. In the UAE, a country with a hot arid climate, these strategies have relevant importance. The aim of this study is to design an innovative parametric/dynamic façade in a new building, to be built on the United Arab Emirates University Campus, AL Ain, Abu Dhabi, UAE. The new structure is an additional library building (with additional functions to the current building). The design shall be based on the region's architectural heritage. The modelling and simulation tools used are Rhino and plug-ins like Grasshopper. Furthermore, an optimization process of the parametric/dynamic façade is conducted. Based on the energy simulation results, the application of the innovative parametric/dynamic façade brings a reduction of 25% in the energy consumption of the building. In addition, the daylight improvement by the application of this façade is 44%. This research brings innovation in terms of the advanced tools used in calculating several parameters for the advanced façade and the process from concept to modeling and simulation. These findings are promising for regional industry due to the advanced tools and methods used. Moreover, it shall help the local authorities such as Abu Dhabi Municipality achieve the sustainability goals 2030.

Keywords: parametric architecture; energy simulation; LEED; rhino; grasshopper

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1. Introduction

UAE is classified as the 5th highest country in the world regarding energy consumption per capita [1]. Thus, it is necessary to take some actions and apply strategies to reduce the buildings' energy consumption. More than 40% of the total energy is consumed by residential and commercial buildings as electricity. [2]. Therefore, this study aims to contribute to the design of an innovative parametric/dynamic façade with the main scope of reducing energy consumption in addition to improving daylight and visual connection (indoor–outdoor).

The digital revolution is the outcome of the extensive integration and overlap between several technological revolutions. The first revolution was the invention of the personal computer, the second was the World Wide Web, and the third is the tremendous advances in media technology. Parametric design is one of the modern computational/digital design systems. It is a process based on algorithmic thinking that is able to coordinate different data and types of information, which are introduced into the program to be translated into formulae that are then applied to the design [3].

1.1. Parametric Design

Parametric architecture refers to a number of parameters (variables) pertinent to a particular design. The shape and proportions of the design can be controlled and altered by altering the values of these factors [3]. Around 2008, parametric architecture began to gain popularity as a concept or theoretical idea in the field of architecture. This development coincided with the emergence of new communication technologies that have been widely adopted in recent years thanks to the digital revolution, as well as the development of digital design tools [4]. A final architectural product that is coherent in aspect can be produced by changing parameters to make an unlimited number of identical designs [3]. The formation or apparent shape of a parametric design is simply an architectural design created with the aid of sophisticated mathematical programs that read parameters and carry out intricate computations beyond the capabilities of the human intellect. A computational design approach is one of the earliest approaches to design that are known to all cultures. Geometric shapes with simple-to-recognize visual characteristics were created using mathematical approaches and calculations [3]. The design of systems using clear principles, where the geometry and performance requirements are mathematically and technically pre-rationalized using sophisticated computing techniques, is known as parametric architecture. Contemporary design practices have developed three different parametric design paradigms: Parametric formalism, which uses complex formal compositions as narrative in parametric techniques; Workflow parametric, using parametric features to automate specific design workflows for projects such as façade design, environmental processes, or structural procedures; Parametric BIM software and processes, which allow architects and engineers to construct virtual models of the building systems and materials [5].

New research provides a collection of global experiences that illustrate the application of various stages of the use of digital design tools, highlighting the ultimate traits and similarities of the products. Particularly, the architectural design typically separates the analytical and creative processes, enhancing their interaction and, in some situations, making them into the same thing. This method closes the gap between the concept and the aim of the design by making portions of the process of design explicit and evaluable [6].

In terms of appearance, parametric shapes mimic both organic and inorganic natural phenomena, which are the outcome of natural elements developing on their own. Instead of the forms created by earlier design trends, parametric design creates forms that seem like nature and structures that mimic the biological processes of natural elements [1]. This design strategy, also referred to as "bio morphism", is the outcome of creating structural shapes using a genetic algorithm, which mimics nature's behavior. The two different forms of parametric design are as follows [7]: Systems known as propagation-based systems compute from known to unknowns using a data flow paradigm; datasets of continuous and discrete constraints are resolved by constraint systems. In conclusion, although it is built on rigid shapes like the square, triangle, and circle, the parametric design process is more flexible than the previous design methods. Moreover, parametric architecture provides speedy iteration and higher chance of innovation, higher speed and accuracy, and better design quality with better productivity during the design and execution process [8,9].

1.2. Dynamic Façade

Buildings must provide inhabitants with appropriate interior environmental quality (IEQ) in terms of thermal, visual, indoor air quality (IAQ), and acoustic comfort in addition to shelter. Humans generally spend 90% of their time indoors, and with the recent global pandemic, the significance of building with good environmental quantities has been increasing. According to studies, buildings consume around 34% of global energy, far more than industries and the transportation sector [10].

Most of this energy is spent on cooling and heating, in accordance with the climatic regions and seasons of those areas. Due to the factors listed above, building envelopes play a significant role in the building's energy efficiency. The building envelope, such as the building façade, is responsible for connecting the indoor and outdoor environments, and plays an active role in creating an interior environment that has positive effects on the environment, as well as people's health and productivity. Building façades account for more than 40% of heat loss in the winter and for overheating in the summer, which are factors that have a significant impact on energy usage. Façade orientation and the building glazing ratio, for example, the use of large glass panes and windows, which are frequently used in office buildings, can be greatly impacted by direct solar radiation. Overexposure to the sun's rays damages semi-transparent façade materials visually and increases cooling energy demand [11,12].

One of the most effective methods of integrating indoor and outdoor environments is the use of dynamic façades which adjust sunshine, natural ventilation, and thermal comfort for the inhabitants. They also play a role in reducing the dependence of a structure on ventilation, heating and cooling systems, and artificial illumination and energy requirements in general. For instance, smart glass systems dynamically manage daylight and solar gain by switching between transparent and reflecting modes to control the flow of natural light into buildings. These façades react to changing boundary circumstances by making reversible adjustments to their characteristics [12].

A dynamic façade system is regarded as a key element of a high-performance building envelope that is able to react to environmental cues and attempts to increase occupant comfort and energy usage. Very little historical studies have been done on the development of such systems, even though building design-related research has addressed the technical and design elements of responsive façades [13].

Based on their operating methods, we have those dynamic façade types. User-control Dynamic façade; Light-control dynamic façade; Light projection dynamic façade; Seasonal green dynamic façade; Wind responsive dynamic façade [14].

In a recent study, several scholars and designers from all over the world have proposed the concept of adaptive solar façades (ASF), which are dynamic, modular, and adjustable façades. It has been described as one of the most efficient ways to control interactions between the interior and outside environments to enhance occupant comfort indoors, summer shade and natural ventilation, acoustic insulation, and winter heating. Climate adaptable skins should be different from traditional façades, in that they may modify their features and serve as a mediator between the shifting surroundings [15].

1.3. Cooling Load and Electricity Reduction in Buildings

As is well known, UAE is located in a hot, dry, and humid environment, where cooling loads are high and electricity costs are very high. Research has been conducted on the building's components and the effect of various strategies for reducing the heat loss through the building. A review study [16] that explores the benefits of improving the building's energy efficiency in UAE found that any amount of energy retrofitting for any existing building can reduce the energy consumption and peak power demand as well as in lowering carbon emissions for UAE. For example, based on the previously mentioned review, using a passive system for the building envelope was estimated to reduce the energy consumption of the residential building by 30% [17], while applying advance envelope system, including climatic interactive façade systems and green roof, was estimated to reduce the thermal loads by 20% [18].

One study investigated the effect of using an integrated photovoltaic façade system with transparent Photovoltaic (PV) windows, Building Integrated Photovoltaics (BIPV) on a commercial building located in Al Sharjah. The study found that using the BIPV system reduced the annual electrical consumption for cooling loads by 27.69% and reduced the yearly cost of the energy by 2084 USD [19].

However, a study analyzed the effects of adding different energy retrofitting strategies on a residential building in an automatically calibrated model considering the urban heat island effect in Abu Dhabi [20]. The findings of this study indicate that when shading is introduced, adding cool paint to the roof, adding cool paint to the walls, and adding external louvres to the windows, combined, it can reduce the energy consumption by 25% as compared to the base case.

Additionally, a study conducted by Al Khateeb and Abu Hijleh [21] evaluated the potential of retrofitting an existing federal office building in UAE to become a net zero electricity building. The passive strategies reduced electricity loads by 14.7%, while the active measures reduced electricity loads by 63.2%. The applied PV system covered the reduced energy demand, resulting in a net Zero Electricity Building.

1.4. Energy Simulation in Buildings with Rhino/Grasshopper

Parametric models are easily replicable and easy to update, making them suitable for a wide range of building performance problems and large developments. Their flexibility allows designers to feed the design process with accurate analysis as the project evolves. This study presents a comprehensive parametric modelling workflow developed in Grasshopper to assess overheating, daylight, and thermal comfort in large residential blocks. The parametric nature of the proposed workflow, in conjunction with a lot of outputs and inputs flexibility, expands the modelers' ability to customize their energy studies and improve replicability towards larger schemes [22].

Assessment showed that promising surfaces for BIPV application on those institutional buildings in the central zone presented noticeable shadowing effects from neighboring buildings, high treetops, or even self-shading caused by the building's geometry. Using BIPV systems on façade surfaces could only achieve 2.66% up to 10.56% of energy balance, with higher proportions for taller buildings in tilted PV shading devices. Although the tilted modules harnessed a higher proportion of the annual total available solar irradiation, BIPV arranged vertically could occupy more surface area, thus allowing a higher nominal power. On the contrary, simulation results for BIPV roof applications were rather advantageous, especially for those up to 6 stories high, achieving results higher than 50% of the annual energy balance [23].

A recent study introduces a new parametric shading device for sun-oriented envelopes of buildings in four dimensions. On the basis of the literature review, 4D computational shader systems can be designed and developed. Presently, different shader systems have been designed and investigated in the field. This study examines the design of a specialized shader system that uses independent shading units to respond in four dimensions to the sun to improve the quality of daylight inside buildings during the day and minimize the need for artificial lighting. For daylighting evaluation, several simulation software programs have been developed in the last few decades in various studies. As the current research focuses on the design of a new 4D shader system to improve the lighting efficiency of a building, simulation modeling is the most appropriate and accurate method to use [24].

Thus, new research is an initial phase of designing a two-story wooden house in Kitakyushu District, Fukuoka, Japan. The intended project will undergo a parametric design process for both environmental and structural analysis. Thus, it needs the base case for comparison before and after attempting to seek the potential of efficiency. This research aims to develop a benchmark model as a base case for further comparison needs regarding microclimate and environmental aspects, daylight and sun exposure, view outside, and energy consumption [25].

Furthermore, a new study analyses the potentials of parametric design optimization process over the residential building to achieve more sustainable design, as well as the computational design methodology in the design process to activate the role of the computer in the design process not just as a drafting or visualization tool. It also investigates the essentiality of computational design and the state-of-the-art computer tools like Grasshopper, Octopus, Energy plus, Open studio, Radiance, and Daysim in achieving an optimized parametric design. It also focused on representing the details of parametric-based optimization using genetic algorithms in grasshopper canvas [26].

1.5. Advanced Modelling Tools

A popular software being used by architects nowadays is Rhino/Grasshopper. Grasshopper (graphical algorithm editor) is a plug-in for the 3D modeling program Rhinoceros, which enables designers to create parametric shapes and run simple to complicated modules without the need for scripting expertise. Grasshopper comes with many algorithmic computational launchers to execute different designs and simulations. For example, the Ladybug plug-in and Honeybee are used to execute the environmental simulation [4]. On the other hand, Daysim and Radiance are used to simulate form dynamics, daylight, and glare studies by combining various dimensions and proportions while taking seasonal pattern fluctuations into account [1].

Generative design refers to a design process that utilizes a computer algorithm. With the formulation of parametric algorithms, design results can be automatically generated by computers, which can help designers automatize parts of the design process. The optimal design scheme is then selected via a building energy simulation and optimization process [27]. The Islamic Geometric Patterns (IGP), drawn using modular systems, are based on picking smaller modules or units and repeating them periodically to create a tessellation. This tessellation is made of squares and rectangles, and this method can effectively produce many IGPs. The polygons in the contact method describe the IGPs as two layers of geometric grids, where one is the original layer of IGPs and the other is a polygonal grid [28].

Parametric generative design method can reduce energy cost of residences, and its energy efficient design and AI technology are combined in an early design stage. An algorithm is developed to generate residence design schemes automatically. A parametric generative algorithm is developed to automatically generate design schemes of typical Chinese urban residences based on performance-oriented design flow by summarizing the workflow of architects [29].

The Revit-Dynamo and Rhino-Grasshopper dynamic approaches provide a good foundation for future research and further development. They provide integrated and dynamic feedback during the early design phase and a visual representation of the environmental impact of the various material and component choices using color coding, i.e., red for high emissions and green for low emissions. The excel-based approach provides flexibility to include emerging state-of-the-art or natural, bio-based materials not normally included in generic databases or Environmental Product Database (EPD) platforms [30].

2. Methodology

A six-phase methodology has been developed, in which each phase follows the previous one and is connected linearly to each other. The research took place in Al Ain City. The selection of the site is based on the fast growth of the city and the importance it has played in the country's development. The UAE a has hot arid climate. Al Ain is a city located near the Jebel Hafeet Mountain on the border with Oman. The geographical position of the city impacts the climate; therefore, Al Ain has a lower humidity level than the coastal cities such as Abu Dhabi, Dubai, Ras al Khaimah, or Fujairah. The data used for this research is based on information taken from the UAEU University and from site observation. The modeling evolves into two main lines; the base model, and the upgraded model, by applying the parametric/dynamic façade. The obtained results are analyzed, and the application of the advanced façade is evaluated (Figure 1).

The main steps followed in the study are as below:

- Site evaluation and building program.
- Climate analysis.
- Design process of base case (organic architecture).
- The design process of the innovative Parametric/Dynamic Façade.
- Modeling and simulation of the base case (organic architecture).
- Modeling and simulation of innovative Parametric/Dynamic Façade.

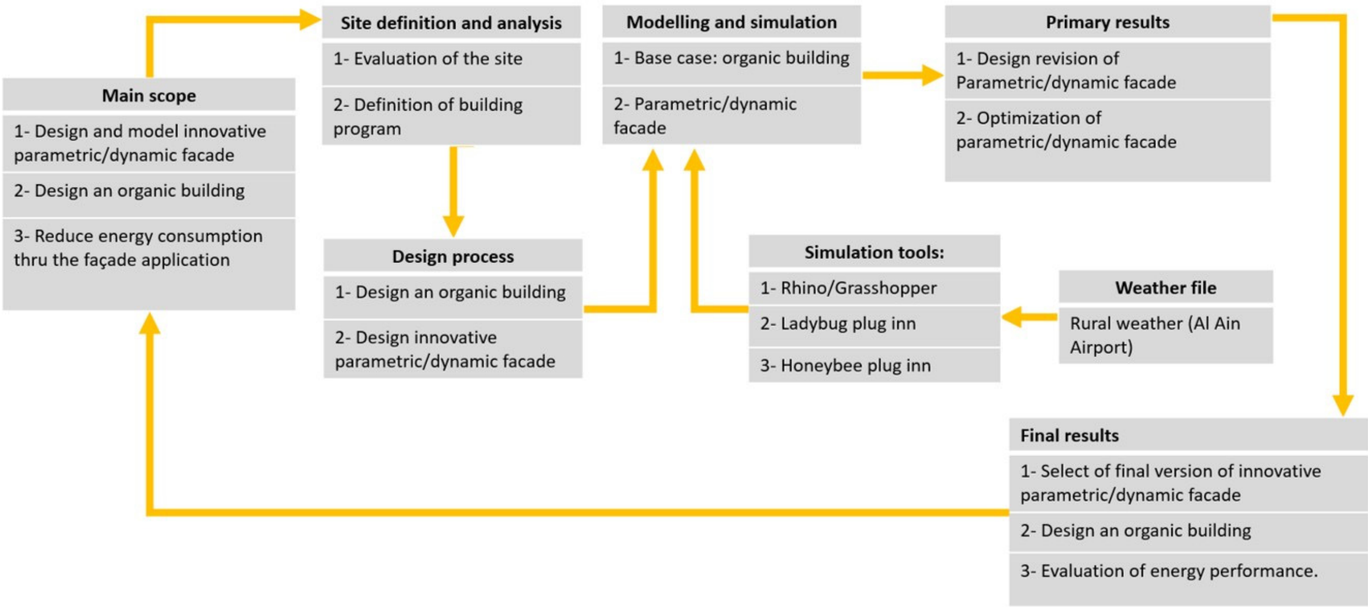


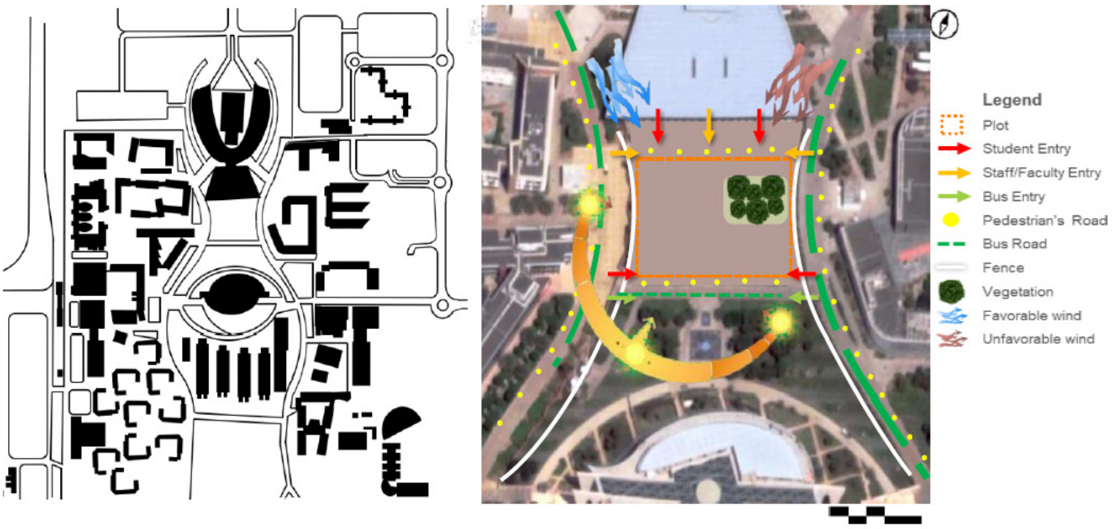
Figure 1. Methodology in a schematic view.

2.1. Site Analysis and Building Program

The site location and surroundings are shown in Figure 2. Site analysis was done (Figure 3) and decisions were made based on the study. The soil type here is Tropopsamments, which has low dunes and a range of suitability. The soil is not very strong, but there is no special treatment needed for the soil. The decision is to use a type of specific foundation, a shallow foundation, and this will achieve the requirement. In the topography part we will have flat land and no hills. This area is totally straight and has no bumps or hills. According to the existing landscape elements, construction may cut existing trees and remove water bodies. Taking advantage of greenery (Figure 4), we integrated design with some of the exiting greenery. There is no pedestrian access to the site for students, as student access is only through the library. However, there is bus access, and some staff entries could be used for students as well. The space is enclosed by a fence which must be removed and a new entrance must be provided for students. Since the site is surrounded by a building, the only source of noise is the bus sound. Therefore, sound insulation is needed in the building, and some fountains can be added to reduce the amount of noise surrounding the space. Figure 5 shows images of the façades of the buildings surrounding the selected site. This analysis was done in order to create an architectural connection with the new building [31].

(**a**) (**b**)

Figure 2. Site analysis (**a**) city level, (**b**) neighborhood level.



(a) (b)

Figure 3. (**a**) Surrounding building footprint analysis, (**b**) site analysis map.

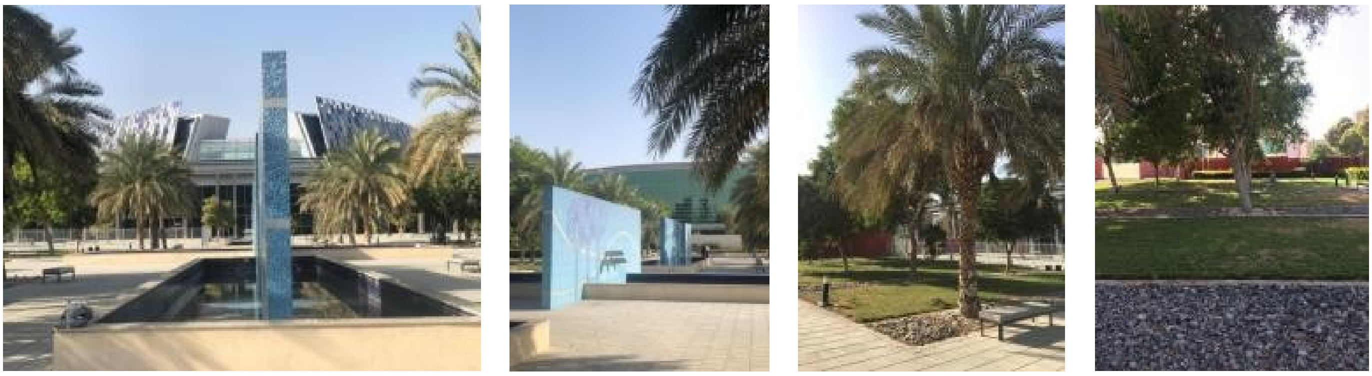


Figure 4. Site images from UAEU campus.

Figure 5. Images of the façades of the buildings surrounding the selected site.

The existing UAEU Library has been analyzed for its structure, spaces, and areas in order to help the library extension area program and to analyze necessary or unnecessary spaces in the extension. The UAEU existing library has spaces such as a café area and carrels at the beginning of the left entrance arrow in the red color (Figure 6). The reading area is the most used space in the building. At the second main entrance into the library, the reception will be at the entrance to address any questions or offer help. In the southeast, the library will have common spaces, meeting rooms, and kitchens. Finally, the doors placed in the southeast take us to the site we are analyzing. The library is considered a long-span structure, with a structural system of steel posts and beams. Steel columns are 0.15 m per 0.15 m, and their spacing is 16.8 m. The structure shows the horizontal and vertical grids shown in the columns. The library structure is a very symmetrical structure that makes it easier for the load to be handled.

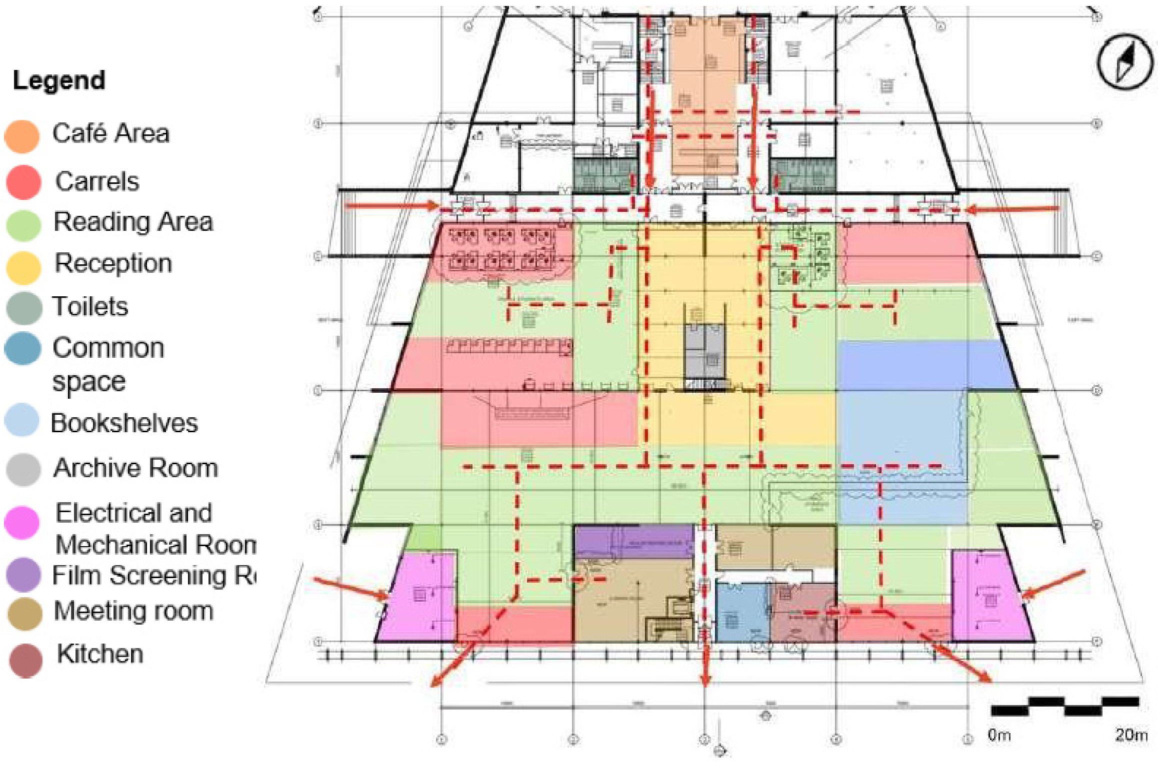


Figure 6. Plan analysis of the existing library.

2.2. Climate Analysis

The UAE has a hot arid climate. Al Ain City has an average yearly temperature of 28 °C. The warmest month is July, with an average of 36.4 °C. In January, there is an average of 17.7 °C (Figure 7). Al Ain has an average of 129.41 h of sunshine per month. June is the month with the highest average number of sunshine hours, with an average of 12.11 h. January has the lowest values, with 9.18 h of sunshine (Figure 8). Due to its location towards the inner part of the country (border with Oman), the city has lower levels of humidity. The month with the highest relative humidity is January (51.08%), and the month with the lowest relative humidity is May (20.93%) (Table 1) [32].

Table 1. Average 10 years data for temperature, humidity, and precipitation for the city of Al Ai.

	January	February	March	April	May	June	July	August
Avg. Temperature °C (°F)	17.7 °C (63.8) °F	19.9 °C (67.8) °F	23.5 °C (74.2) °F	28.5 °C (83.3) °F	32.9 °C (91.3) °F	35.1 °C (95.1) °F	36.4 °C (97.5) °F	36.2 °C (97.1) °F
Min. Temperature °C (°F)	11.3 °C (52.4) °F	12.9 °C (55.2) °F	16.1 °C (61) °F	20.6 °C (69) °F	24.7 °C (76.4) °F	26.6 °C (79.9) °F	28.8 °C (83.9) °F	28.9 °C (84) °F
Max. Temperature °C (°F)	23.9 °C (75) °F	26.5 °C (79.7) °F	30.5 °C (86.9) °F	35.8 °C (96.4) °F	40.6 °C (105) °F	42.8 °C (109) °F	43.3 °C (109.9) °F	42.9 °C (109.3) °F
Precipitation/Rainfall mm (in)	9 0	9 0	13 0	6 0	0 0	0 0	3 0	2 0
Humidity(%)	51%	41%	32%	24%	21%	23%	27%	27%
Rainy days (d)	1	1	1	1	0	0	1	1
avg. Sun hours (h)	9.2	9.8	10.6	11.4	12	12.2	12.1	11.7

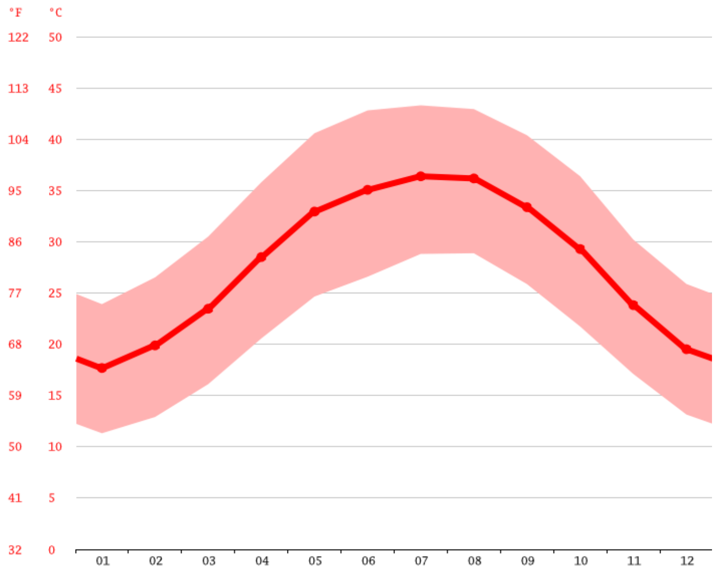


Figure 7. Temperature levels in Al Ain.

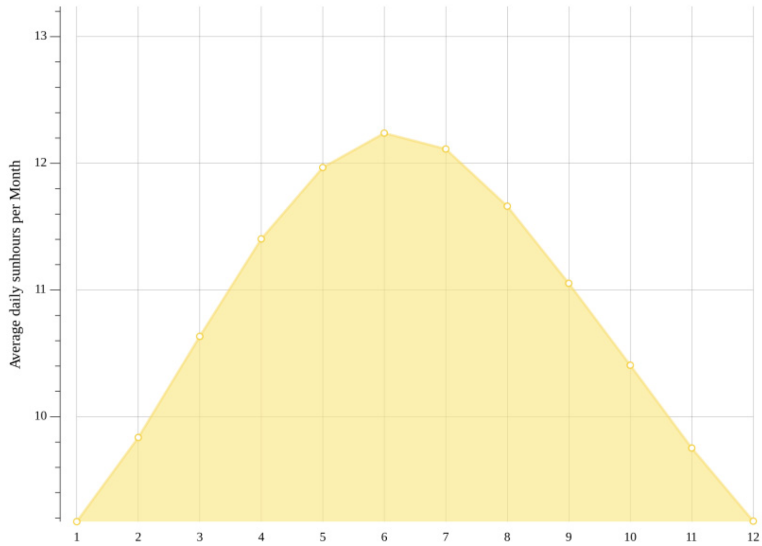


Figure 8. Average daily sun hours per month in Al Ain.

2.3. Design Process of Base Case (Organic Architecture)

The design of the library extension with organic architecture was done with the aim of integrating the building with the landscape that is currently on site (Figure 9). This building design is considered the base case as it refers to the building prior to the parametric/dynamic façade. However, the elevation also shows the integrated façade. The design process of the main building is described as follows. The landscape development has the actual number of trees already found, which is equal to the ones shown according to the type as illustrated. The program and function plan have all the areas organized, and it will be 1034 sqm. However, there are some strengths and weaknesses in this design. The studies show that the strengths of this building are its ability to reflect art and creativity, its flexibility, its integration with the landscape, and the integration of space that gives a comfortable feeling. There are also some weaknesses in the development of this project. For example, the largest weakness found is the load of the dynamic façade. The figures below illustrate schematic drawings of the chosen development. The plans and the 3d are shown in Figures 10 and 11. Meanwhile, Figures 12–15 show the building elevations from different directions [33].

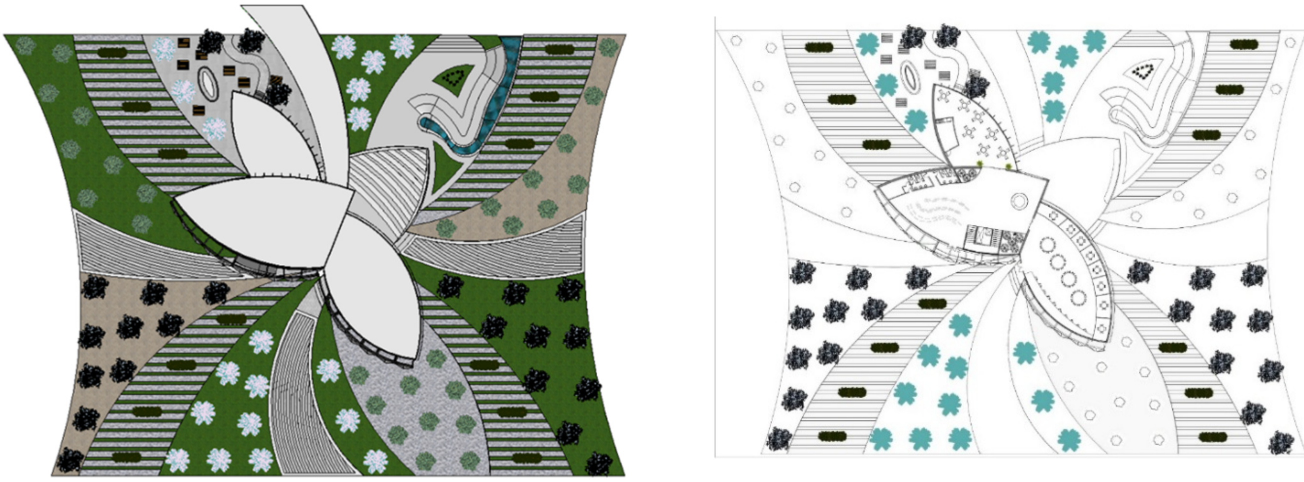
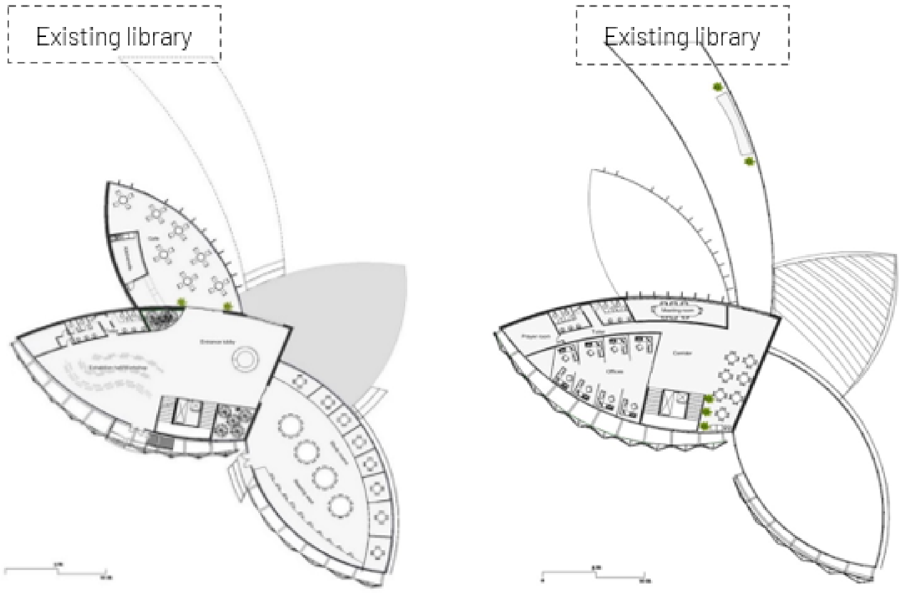
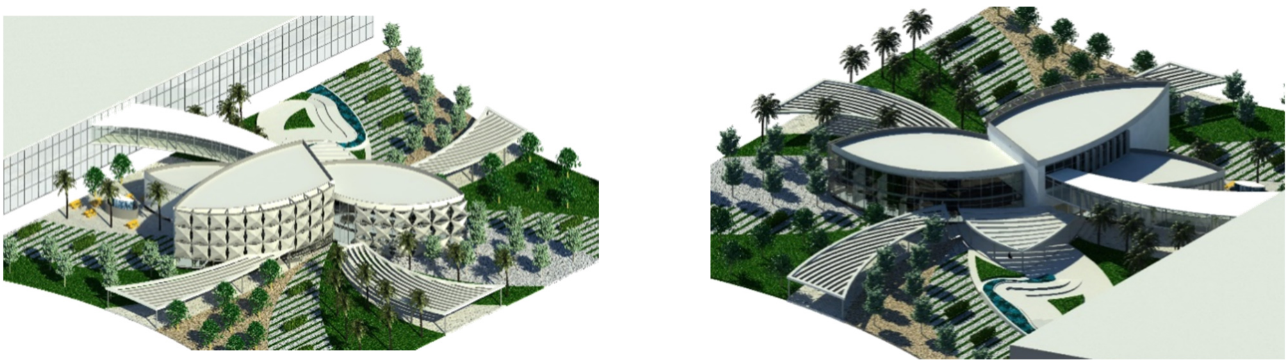


Figure 9. Floor plan with landscape.



(**a**) (**b**)

Figure 10. (**a**) Architectural ground floor plan, (**b**) architectural first floor plan.



(**a**) (**b**)

Figure 11. 3D rendered eye bird Views (**a**) south view, (**b**) north view.

Figure 12. South elevation.

Figure 13. East elevation.

Figure 14. West elevation.

Figure 15. North elevation.

2.4. Design Process of Innovative Parametric/Dynamic Façade

The design of the elements of the façade is inspired by IGP (Figure 16). There is a great history of use of IGS patterns in the Middle East. The use varies from decorative (in entrances of buildings, façade walls) to functional (mashrabiya application). The mashrabiya as an architectural element allowed houses to have privacy, shading, and natural ventilation. This element of passive sustainable strategies combined with advanced tools such as Rhino Grasshopper are the basis of this research on the parametric/dynamic façade. Based on the ISG, the design of the main unit of this façade evolves by adding other parameters such as size of unit (linked to the technology of application), material, opening distance, and connection to the library extension building [28,34].

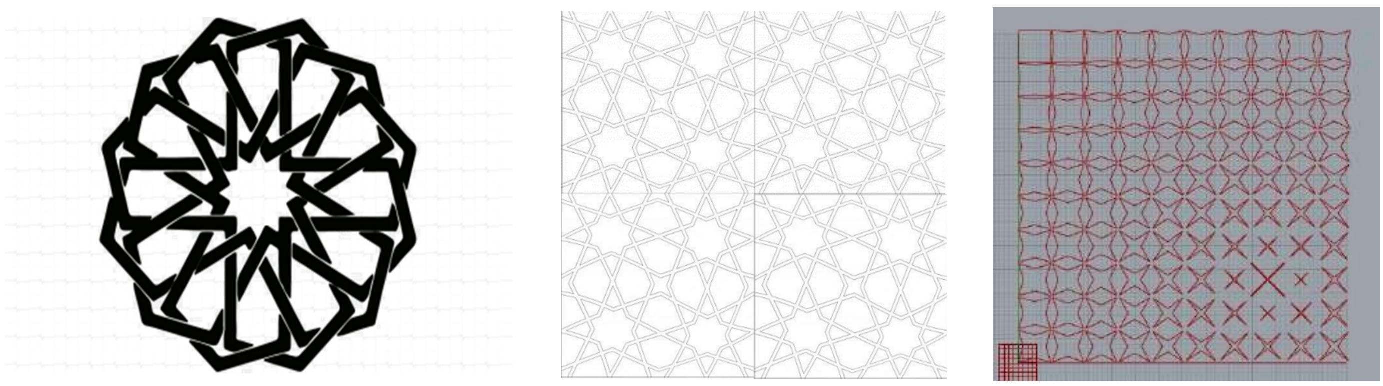


Figure 16. Design evolution of the parametric dynamic façade.

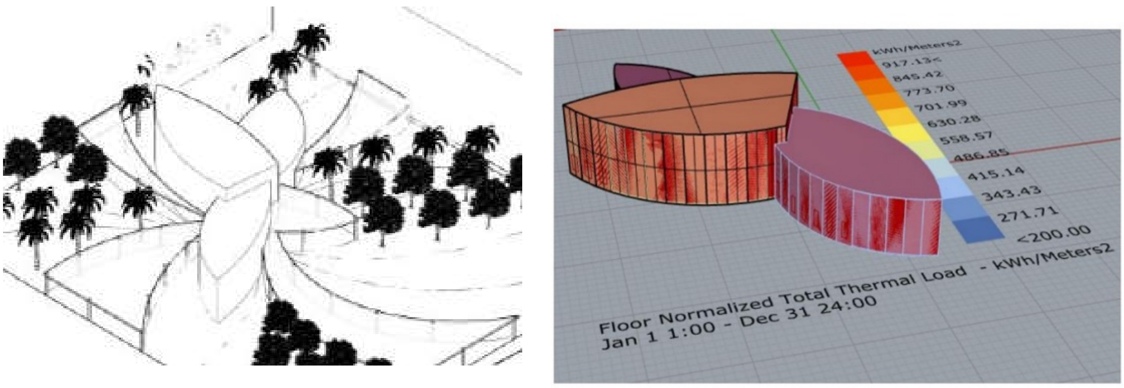
The material selected for this façade is Polytetrafluoroethylene (PTFE), which is a coated fiberglass ventilated fabric mesh. In fact, PTFE features aesthetics, longevity, and functionality. An advantage for this material is that its coating is smooth, which means it is self-cleaning with rainwater and dust does not deposit on its surface. This material highly resists extreme UV radiation, heat, temperature variation, sandstorms, and fire. The U-value considered for this façade is 2.0 Wm^2/k. PTFE allows natural daylight and shades the building from harmful sunlight and glare simultaneously. As a matter of fact, it reflects 75% of sunlight, absorbs 10% of sunlight, and transmits 15% of sunlight [35].

2.5. Modelling and Simulation

The modeling and simulation process of both the base case (new library extension building) and the innovative parametric dynamic face was done with two main tools: REVIT and Rhino [36,37]. The REVIT was helpful in the initial stages of concept, and in Rhino the advanced modelling and simulations took place. The combination of both models was done later on to evaluate the impact of the façade on the several aspects analyzed (solar radiation, daylight, energy consumption).

2.5.1. Modelling and Simulation of the Base Case (Organic Architecture)

The modeling and simulation process of both the base case (new library extension building) and the new library was initially completed in REVIT. The main volumes and the integration with the surrounding landscape were done in REVIT. In this tool, the definition of the main volumes was done in relation to the surrounding buildings. However, all the simulations are done in Rhino and several plug-ins such as Grasshopper, Ladybug, Honeybee, and Daysim (Figure 17).



(**a**) (**b**)

Figure 17. (**a**) Model of the library extension in REVIT, (**b**) simulation in RHINO.

2.5.2. Modelling and Simulation of Innovative Parametric/Dynamic Façade

The modeling process of the selected pattern starts with the main points of the geometry. Next is to draw the pattern, with each point defined. To create the mechanism of folding inwards and outwards, a point is defined at the center away from the plane to allow for folding distance (Figure 18). The mechanism of the pattern is to fold inwards and outwards based on the sunlight [38,39]. First, before drawing the pattern, the surface needs to be defined and divided up according to its dimensions. The script used in the rhino software is shown in Figure 19. This script has been modified and adapted continuously based on the optimization process based on the daylight analysis, solar radiation, and impact on indoor–outdoor visibility. Figure 20 shows the geometry of the structure after the connection of all points defined earlier in the process [40].

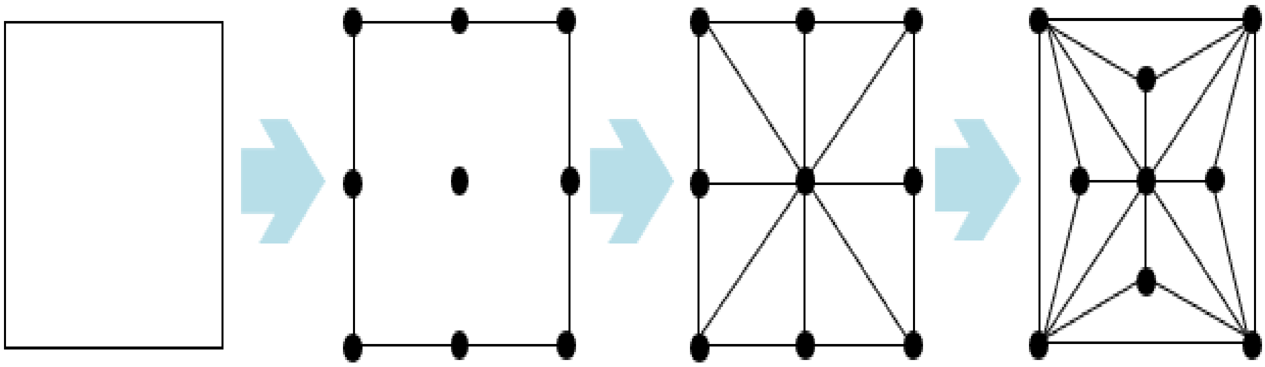


Figure 18. Alternative 1, folding mechanism. Development.

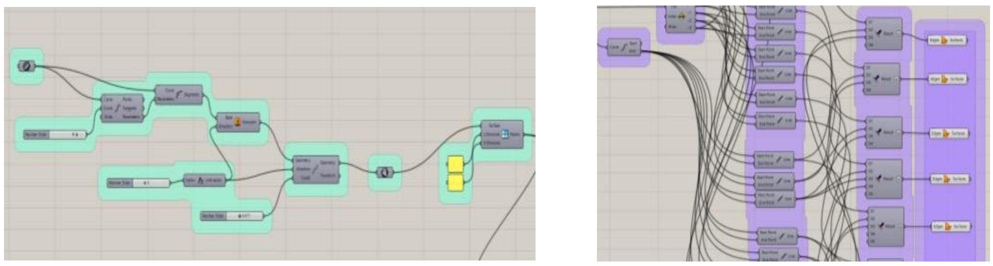


Figure 19. Alternative 1 script. Grasshopper script.

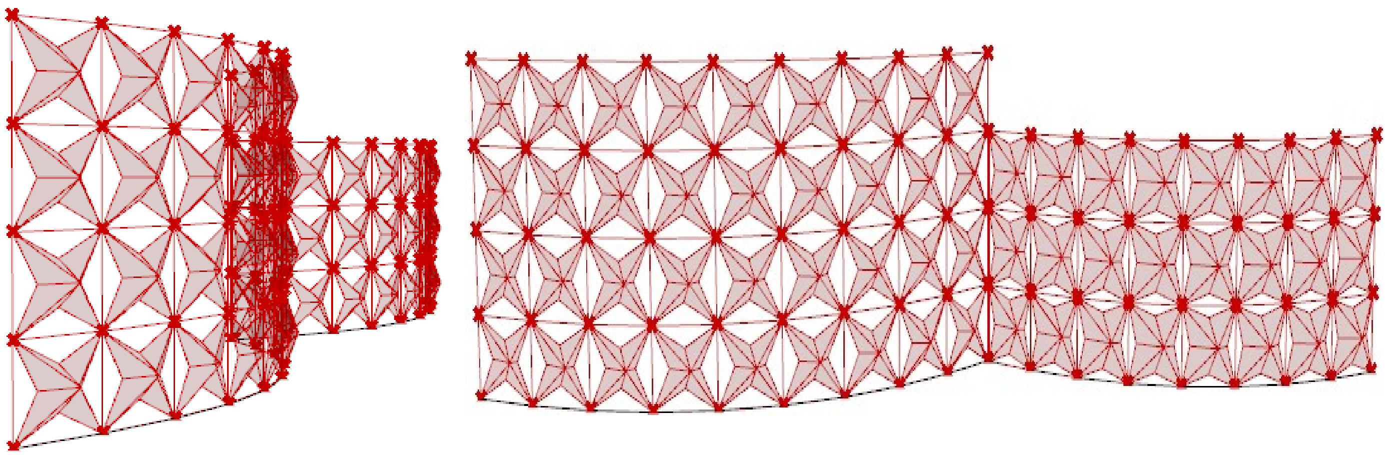


Figure 20. Alternative 1. Grasshopper Generated.

2.5.3. Optimization Process

The optimization process of the innovative parametric dynamic façade is based on several points: improving visual connections between indoor and outdoor; minimizing the solar radiation in the façade of the newly constructed building (extension of the library); optimizing the indoor daylight based on the sun movement during the day; minimizing the energy consumption in the building (based on the reduction of the air conditioning and lights).

In each of the above steps of parametrization, the design of the unit was modified accordingly. As this process was quite time-consuming, the primary results were analyzed, followed by simulations for each parameter considered, and then all parameters were simulated together.The first parameter is defined by improving the visual connection between indoor and outdoor. This definition indicates that the façade units should remain open for the longest possible period of time during the day (Figure 21). Also, these definitions were used to determine the location and size of the units. A building's structure has been designed to prevent obscuring the visual connection between the indoors and the outdoors.

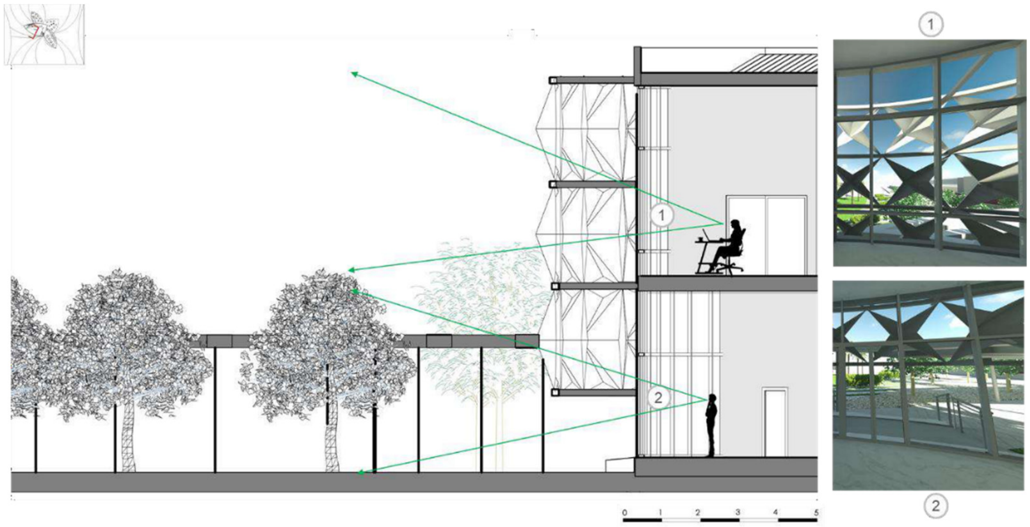


Figure 21. Visual connection indoor–outdoor.

The second parameter is defined by minimizing the solar radiation on the façade of the new building (extension of the library). This study targeted the peak hours of the library, which were determined by questioning the administration of the existing library; the peak hours were found to be from 8 a.m. to 3 p.m.

In addition, the target was the two solstices, which are in June and December, and the equinoxes, which are in March and September, specifically on day 21 of each of those months, which is the most critical. The analysis has been done using the ladybug plug-in in grasshopper, for the peak hours and the months specifying the day. Moreover, the focus was on the sun radiation on the south façade, where the dynamic façade is applied to help minimize the surface area of the dynamic façade and place it at the most critical points receiving the highest radiation (Figure 22). The solar radiation of the façade is also linked to the daylight, as per the paragraph below.

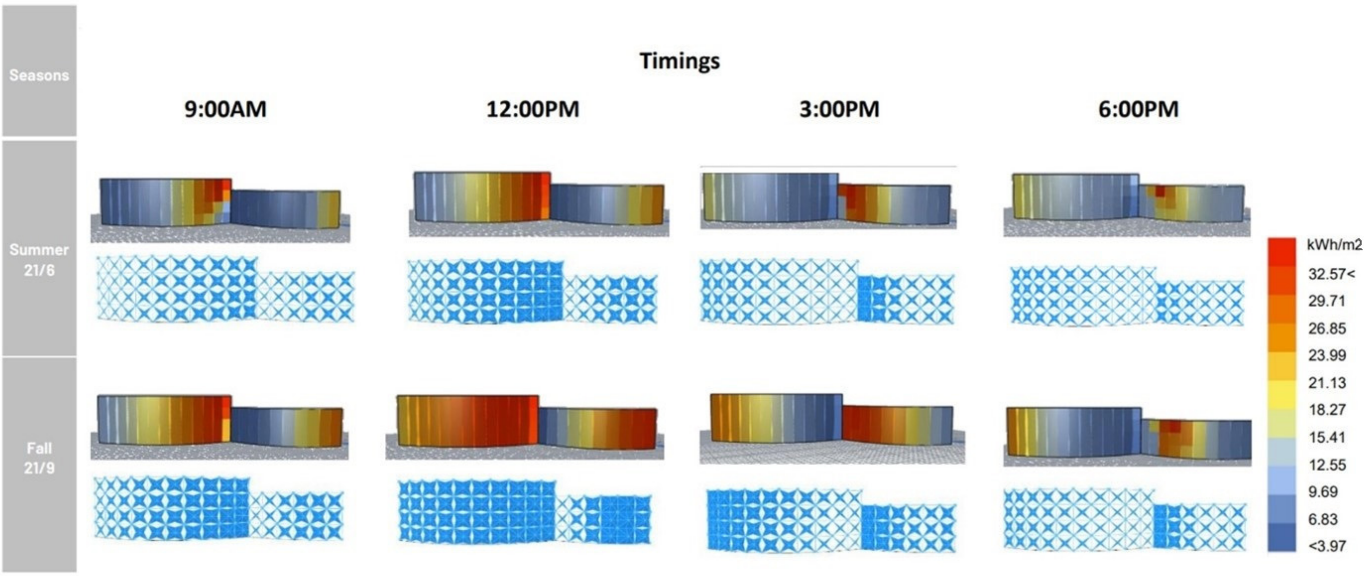
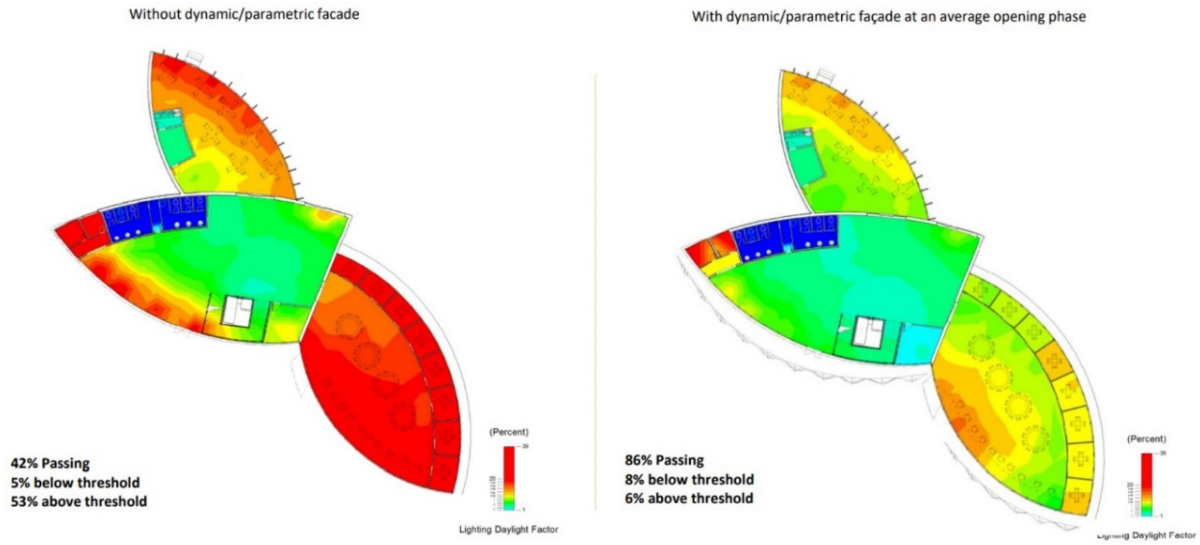


Figure 22. Analysis of the façade during the summer and fall in pique hours based on the solar radiation.

A daylight simulation was carried out for the internal spaces in order to better understand the openings of the parametric dynamic structure. The daylight factor is set in the tool based on the Abu Dhabi regulation. Figure 22 shows the analysis of the solar radiation on the façade before the application of the structure, linking it with the needs of the opening's timing. Figure 23 shows the indoor direct/indirect natural light analysis, (a) without façade, (b) with façade. It is important to evaluate the sunlight passing inside the building to achieve the parametric/dynamic façade's objective and to achieve the visibility requirement provided by the client. Other than that, daylighting strategies that were implemented in the project need to be verified for their performance and efficiency. The strategies include the use of curtain wall systems with double glazing and low-e, shading devices with NE and NW orientations, the use of dynamic/parametric façades, and the placement of the openings and fenestrations. All of these strategies aid in controlling the sunlight admission to reduce artificial lighting, save energy for the building, and help in creating a visually stimulating and productive environment for the users of the extension.



(**a**) (**b**)

Figure 23. Indoor direct/indirect natural light analysis, (**a**) without façade, (**b**) with façade.

The daylighting was evaluated through the daylight factor analysis. A Daylight factor is an analysis that calculates the average illuminance on all surfaces from a working plan (80 cm above the ground level). The outcome is in percentages, with the target range being from 2–5%, with anything lower than the target being poorly lit and likely needing artificial lighting, and any value above 5% considered to be excessively lit and will cause problems with overheating and glare. According to the USGBC and LEED rating systems, the building surface area needs to pass at least 75% of the critical visual tasks to achieve a well-lit indoor environment. For the project, the daylight factor was worked out in two ways: with and without the dynamic/parametric facade.

2.5.4. Energy Simulation

The energy simulation showcases the energy absorbed and consumed by the model's surfaces, allowing the infiltration of solar radiation through the openings, and how much the energy can be blocked through the use of shading devices or any external site context. Using Rhinoceros 3D and Grasshopper, the outputs from the simulation (building, shading devices, and context) and the EPW file (location) will provide information that allows assessment. Materials or u-values are specified, as is the analysis period, which is a whole year. These parameters all contribute to the energy analysis.

The energy simulation will run for the project without the use of the dynamic/parametric façade, and with a façade at a certain opening static state, and finally, it will be calculated as a changing and dynamic façade.

The project needs to consider sustainability to act as a smart building and achieve credits in the ESTIDAMA accreditation rating. The building needs to accommodate photovoltaic panels to generate solar energy. It has a roof surface area of almost 660 sqm, and it can reach up to 835 sqm if the extension bridge is also included. For an annual solar study, a preliminary and brief analysis was performed using Revit. According to the simulation, solar radiation can produce 225,530 kWh/year of PV energy (Figures 24 and 25). The generation of solar energy is related to the products of PV modules and the system. According to UAE regulations, the maximum nominal power that is allowed to be generated in the UAE is 100 kWp. With the use of the PVSYST software program, a simulation of the solar system product was done for this project by using the maximum nominal power (Table 2).

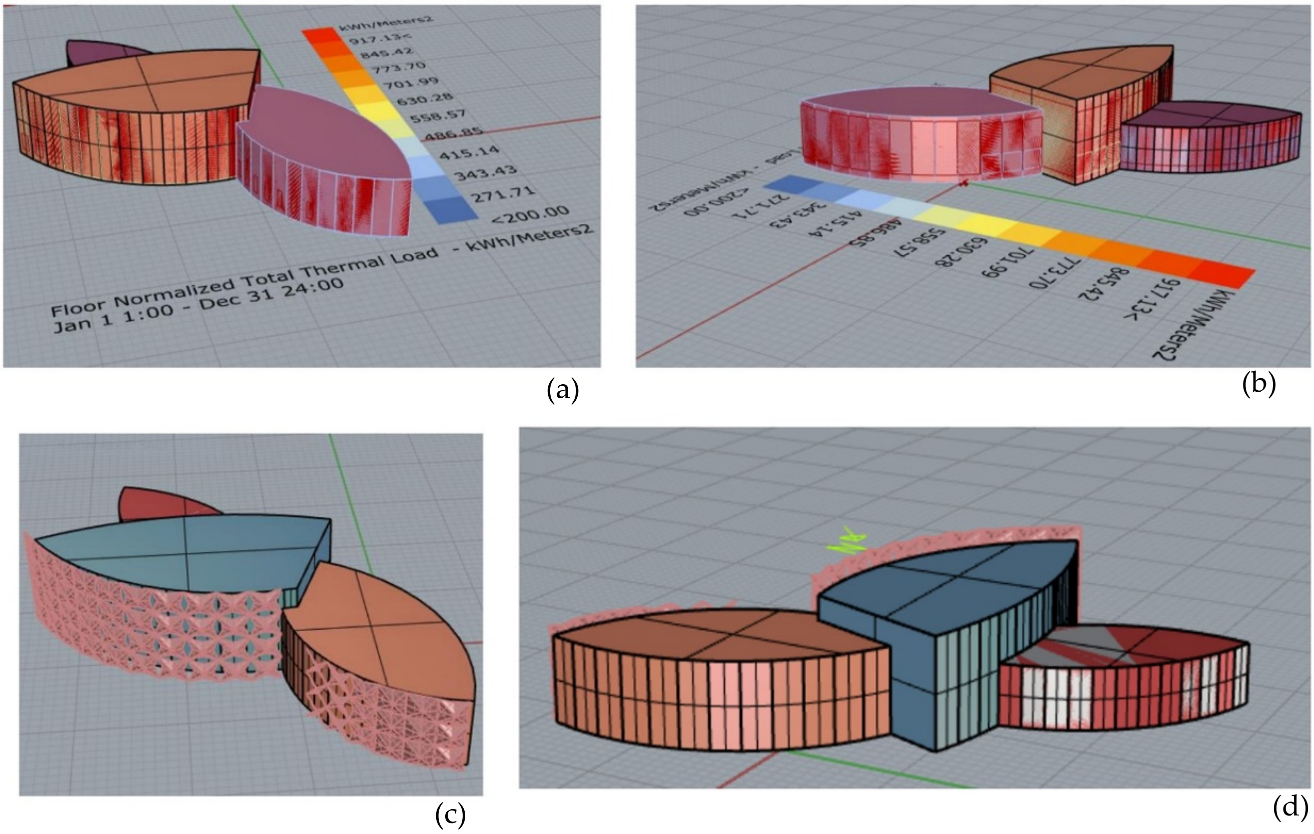


Figure 24. Energy models: (**a**) south view before parametric façade; (**b**) north-east view before parametric façade, (**c**) south view after parametric façade; (**d**) north-east view after parametric façade.

2.6. Tools Analysis, Advantages, and Disadvantages

Rhinoceros is a commercial 3D software used widely in architecture, along with a plug-in called Grasshopper. Among other plug-ins, Grasshopper helps analyze several aspects of the building's design and performance. Moreover, grasshopper simplifies design complexities that exceed conventional 3D modeling and can reference geometry objects in rhino such as points, curves, and surfaces. The online community of this software is quite large and active, therefore there is a possibility to update the Python language scripts in real time. Figure 26 shows that the grasshopper can be used to make calculations about the facade, plan, optimization process, energy use, or structural design. In this image, the complexity of the script is shown (for illustrative purpose only). The different steps are linked to each other until the final results of the simulation are obtained. While working with the tool, identifying the errors was visible immediately, enabling fast modifications to the script.

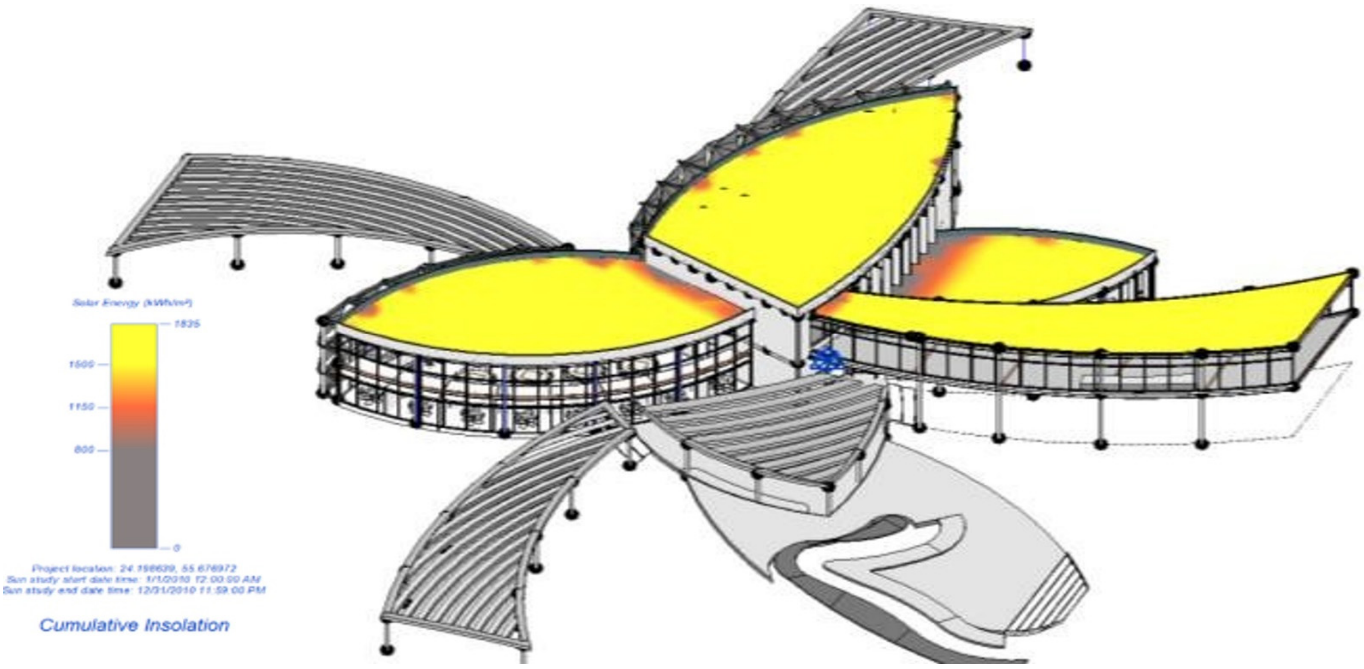


Figure 25. Solar radiation calculation of the roof for PV application.

Table 2. Summary of solar energy system.

Geographical Site	Solar System	PV Panel	Inverter
Al Ain, UAE (24.20°, 55.68°)	Grid-connected System	• Tilt/Azimuth: 24°/0° • number of modules: 170 units (10 strings × 17 in series) • Module area:465 sqm • Pnom total = 99.5 kWp	• number of units: 5 units • Pnom total = 75 kWac • Pnom ratio = 1.33 • Operating voltage = 380–850 V
Produced Energy	181.8 MWh/year	**Specific Production**	1828 kWh/kWp/year

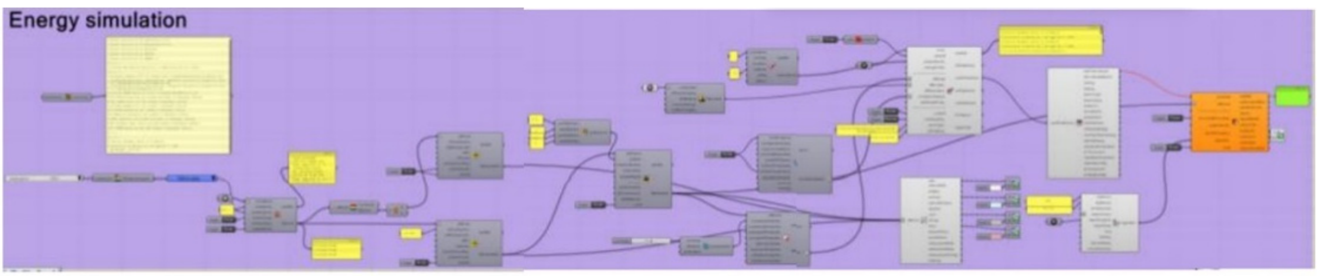


Figure 26. Python language script for Grasshopper, energy simulation (illustrative purpose only).

3. Results

3.1. Innovative Parametric/Dynamic Façade

The analysis was done using the ladybug plug-in in Grasshopper. We plugged in the peak hours and the months, specifying the day. The dynamic façade was applied to help us minimize the surface area of the dynamic façade and place it at the most critical point receiving the highest radiation, which is the south façade [37,41]. The option selected, which is Islamic geometry inspired, was generated in Grasshopper and adjusted based on the library's design. It is applied on the south façade, where the most shading is needed. First for the mechanism, the façade responds to sunlight. It folds inwards or outwards to some extent based on the amount of sunlight according to angle and surface exposed. The following three figures illustrate the operations on the whole façade surface. However, the operations will vary on each part of the façade according to angles in reality [42,43].

As shown in Figure 27, each unit of the dynamic façade has a size of 2 m by 3 m. The material selected for the units is PTFE, which allows natural daylight and shades the building from harmful sunlight and glare simultaneously. The assembly and structure of the dynamic façade is illustrated in Figure 28.

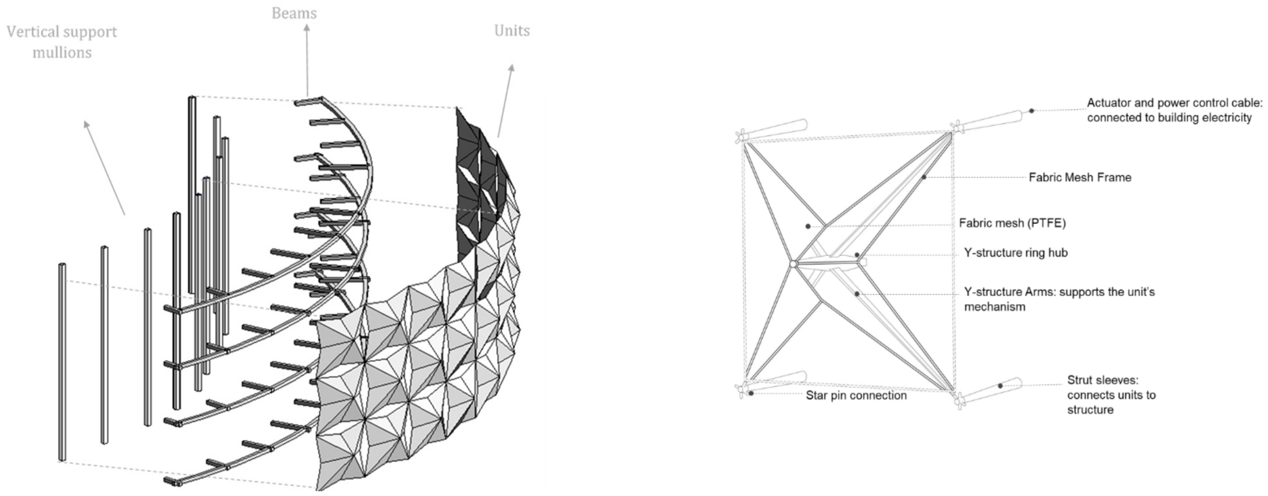
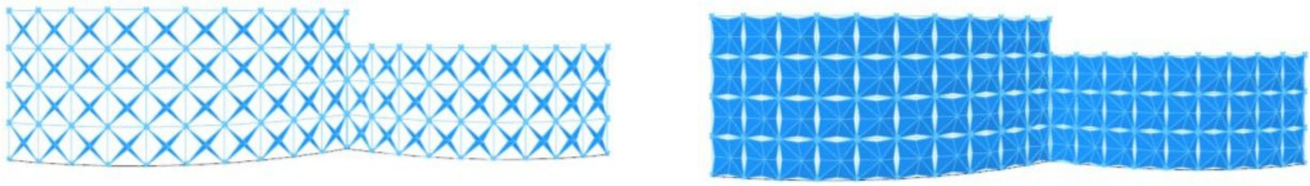


Figure 27. Details of the parametric dynamic façade.



(**a**) (**b**)

Figure 28. (**a**) Opened operation, (**b**) closed operation.

3.2. *Design of Organic Building with Innovative Parametric/Dynamic Façade*

Based on the process of design, modelling, and simulation, the organic building design with an integrated parametric dynamic façade was achieved. The visual connection between indoor and outdoor is achieved with the adjustment of the façade unit size and opening. As a result of the application of the innovative façade, the indoor lighting has been improved by 44% (Figure 29).

Figure 29. Modules of dynamic façade with different phases of movement.

3.3. *Energy Simulation Results*

Based on the energy simulation results, there is a reduction of 25% in energy consumption in the building. If the PV panels are added to the energy reduction, then the electricity savings will reach 70% (Tables 3 and 4). This due to the large areas in the roof where the panels can be added (Figure 30). Additionally, there is a benefit impact on the environment by using the dynamic façade and the glazing systems in the building that can be enhancing the sun light entrance without the usual heat found in the UAE climate. This will help in reducing the energy used by reducing artificial lighting [44].

Table 3. Energy simulation results.

		Total Energy (kWh)	Total Energy (kWh)
Without dynamic/parametric façade	Total Site Energy	298,148.82	447.17
	Total Source Energy	392,486.80	588.65
With dynamic/parametric façade at an avg opening state	Total Site Energy	208,443.06	312.62
	Total Source Energy	294,788.47	442.13
	Energy Reduction Percent %		25%

Table 4. Electricity cost calculation.

Cases	Energy Demand (kWh/Year)	Electricity Tariff (AED/kWh)	Total Cost (AED/Year)
Without dynamic façade, without solar energy	392,486	0.294	115,391.18
With dynamic façade, without solar energy	294,788	0.294	86,667.67
With dynamic façade, with solar energy	181,800	0.294	36,158.47

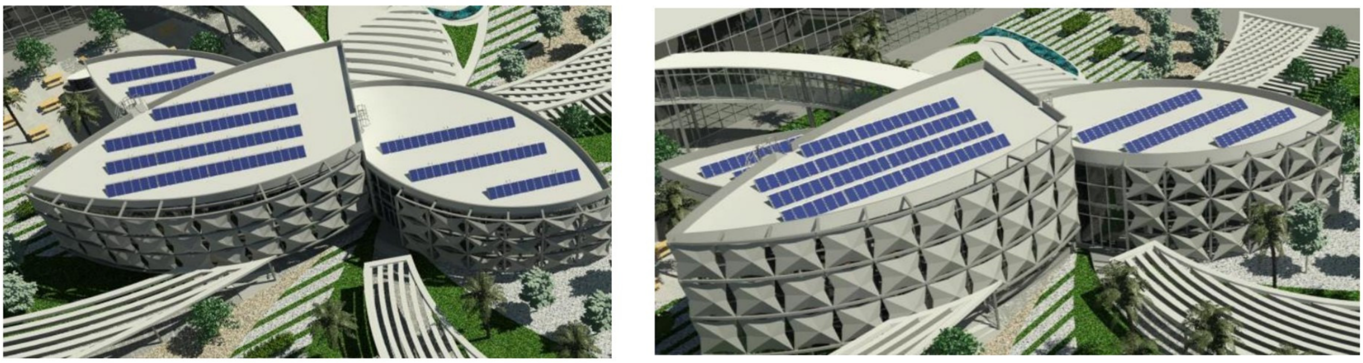


Figure 30. Rooftop images of the applied PV.

4. Discussion

The main focus of this study was to design an innovative parametric dynamic façade for the extension of the UAEU Campus. Based on the results of the energy simulation and natural light analysis, the application of this façade achieved the initial goal.

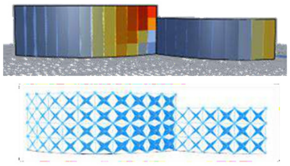
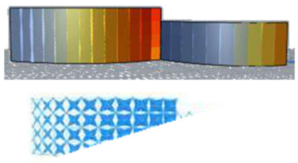
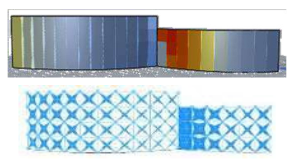
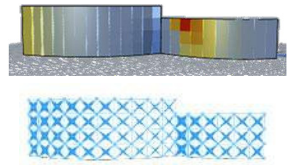
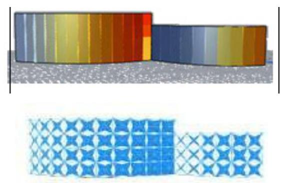
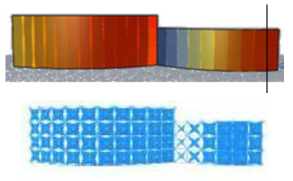
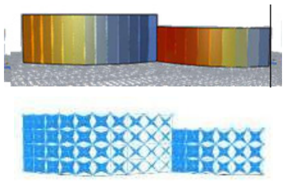
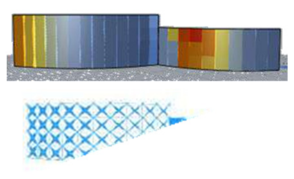
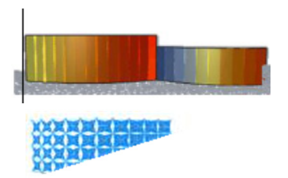
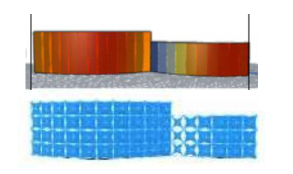
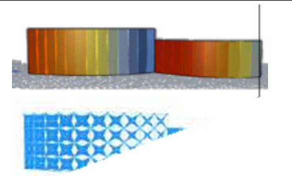
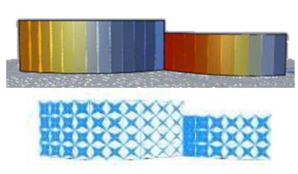
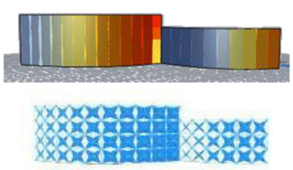
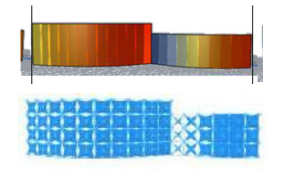
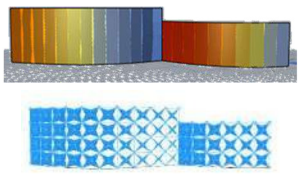
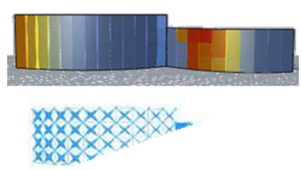
However, there were difficulties in relation to the use of tools for this research.

Adapting the files from different tools: The initial stage of the design was done in REVIT. Adapting this tool to RHINO has difficulties in recognizing some geometries. Therefore, several trials were conducted in order to have defined models from the various simulations conducted.

The optimization process of the façade: The optimization process of the innovative parametric dynamic façade was based on several points: improving visual connection between indoor and outdoor; minimizing the solar radiation in the façade of the new building (extension of the library); optimizing the indoor daylight based on the sun's movement during the day; minimizing the energy consumption in the building (based on the reduction of the air conditioning and lights). Therefore, understanding the Python language in RHINO with the various plug-ins such as grasshopper, ladybug, and Diva was challenging.

The field of application of the Python language and available scripts is very large and needs to be customized according to the specific geometry. Adding more parameters to achieve maximum view from indoor to outdoor, reducing the daylight, and reducing the energy consumption was the most time-consuming section of this study (Table 5).

Table 5. Optimization process based on solar radiation.

	Timing			
Seasons	**9:00 A.M.**	**12:00 P.M.**	**3:00 P.M.**	**6:00 P.M.**
Summer 21/6				
Fall 21/9				
Winter 21/12				
Spring 21/3				

The energy consumption in this study includes the energy from air conditioning and artificial lights. This calculation was not separated, as the aim was to understand the total energy consumption reduction. However, future work is needed to separate the script and detail the energy simulation results.

Gathering initial information: The initial process of finding the information on the existing library and the plans for the future extension was longer than expected. In additiona, the site visit, the initial information on the landscape, and the surrounding buildings needed more bureaucratic procedures than initially estimated.

Future studies can help in improving the coordination of the different tools used in this analysis. The python script used is shared in the open community of rhino/grasshopper, giving an opportunity to other researchers to advance in different aspects of the building design. Furthermore, other IGPs can be analyzed and optimized in order to have a grater variety of parametric dynamic façade designs based on the architectural heritage of the region.

However, despite all the challenges faced in this study, the results of the application of this innovative façade are promising and can be used for other building typologies by modifying the design/optimization process based on the application needs and parameters. Cities in the Middle East can adapt to such an advanced façade design in order to improve their sustainability.

5. Conclusions

The aim of this study was to design an innovative parametric/dynamic façade for a library extension building at UAEU Campus, Al Ain, Abu Dhabi, UAE.

The main findings of this study are that, by applying the innovative façade, there is a 25% reduction in energy consumption of the building and an improvement of 44% in the daylight analysis.

Other important achievements include making a visual connection indoor–outdoor as one of the initial goals. This is in order to integrate the new building into the landscape. Furthermore, the inclusion of the PV panels on the roof generates electricity, making a reduction (in addition to the innovative façade) of the total energy consumption of the building of 70%.

This study brings innovation in terms of the software used to design the façade and the process from concept to modelling the final prototype of the façade. The design is based on the Middle East design pattern that was later adapted and optimized for the Library Extension Building. The software used was RHINO, and Grasshopper was a plug-in that made the full calculations possible. Based on the potential design of the parametric/dynamic façade, future work is needed to understand if this concept can be adapted in other buildings around the campus that have excessive glass surfaces exposed mainly to the south orientation. This could cut the amount of energy used by the whole campus by a huge amount.

This research is relevant to the local industry as it can improve façade technology by using advanced tools. The Parametric Dynamic Façade drastically improves energy savings in the building, and therefore, the field of application is quite large and relevant in the Middle Eastern new cities. Furthermore, it will assist local governments, such as Abu Dhabi Municipality, in meeting their sustainability targets by 2030. The Abu Dhabi Sustainability initiative includes an agenda of goals to be reached by 2030 in alignment with the 17 Sustainability Goals of the United Nations. Goal number 11: Sustainable Cities and Communities is where this study can contribute the most. This goal is aligned with the Sustainable Environment and infrastructure in the National Pillar Agenda [44].

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Conflicts of Interest: The authors declare no conflict of interest.

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