Integrating Parametric and Generative Design for Enhancing Thermal Comfort and Natural Lighting in Contemporary Domes Design

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Abstract

Domes are a type of construction that developed in response to architectural design demands. It was considered a design solution for large spaces without columns. However, due to the development and diversity of dome formation and uses, domes have not adequately exploited their environmental role. In this regard, finding a methodology and a working mechanism to design the dome compatible with the environment became necessary. The method will find environmental solutions for users inside domes regarding thermal comfort and appropriate natural lighting. The research problem is that while parametric and generative design assisted in producing the variety and various shapes of domes, The dome shapes may not adequately investigate their environmental role throughout the design process. There is no practical method to study their thermal comfort and natural lighting to reach the most applicable dome shape. The primary purpose of the research is to develop the design of domes by finding a specific methodology using parametric design and simulation to reach design solutions for domes covering various areas that achieve thermal comfort and natural lighting in addition to the functional aspects. The research's importance is to keep pace with advancements in designing domes using parametric design and simulation programs. The analysis uses the experimental method by using the parametric design, indicators, and parameters of dome design, which produced an unlimited number of domes, therefore the research depends on multi-objective optimization to find the best solutions based on three design and environmental performance objectives, and then verifying the extracted solution by calculating daylight factor and adaptive thermal comfort to reach the optimal solution. The study has reached a set of results: it provided a variety of dome designs in three categories, which reached a comfortable rate of natural lighting and ranged in thermal comfort from 34% to 42%, and it developed a clear methodology for domes in the initial stages based on design, environmental indicators, and parameters to achieve the optimal solution. Simulation programs helped to establish the domes' design process and reach accurate and reliable results. Evolving design and environmental indicators and

Doi: 10.21608/mjaf.2024.295624.3425

parameters of domes will help achieve better outcomes for the dome design that achieves thermal comfort and natural lighting.

Keywords:
Dome design, Multi-Objective optimization, Daylight factor, Adaptive thermal comfort, Simulation tools.

الملخص

تعتبر القباب أحد أنواع المباني التى تطور استجابةً لمتطلبات التصميم المعماري. وقد تم اعتبارها حلاً تصميميًا للمساحات الكبيرة بدون أعمدة. ومع ذلك، نظرًا لتطور وتنوع أشكال القباب واستخداماتها في العمارة المعاصرة، لم تستغل القباب بشكل كافٍ دورها البيئي. وفي هذا الصدد، أصبح من الضروري إيجاد منهجية وآلية عمل لتصميم القباب بما يتوافق مع البيئة، ستعمل المنهجية على إيجاد حلول بيئية للمستخدمين داخل القباب فيما يتعلق بالراحة الحرارية والإضاءة الطبيعية المناسبة. من خلال ذلك تكمن مشكلة البحث في أنه على الرغم من أن التصميم البارامتري والتوليدي ساعد في إنتاج تنوع وأشكال مختلفة من القباب، فإن أشكال القباب قد لا تحقق دورها البيئي بشكل كافٍ خلال عملية التصميم، كما لا توجد منهجية عملية لدراسة الراحة الحرارية والإضاءة الطبيعية للوصول إلى الشكل الأنسب للقباب. الهدف الأساسي من البحث هو تطوير تصميم القباب من خلال إيجاد منهجية محددة باستخدام التصميم البارامتري والمحاكاة للوصول إلى حلول تصميمية للقباب تغطي مساحات مختلفة وتحقق الراحة الحرارية والإضاءة الطبيعية بالإضافة إلى الجوانب الوظيفية. تكمن أهمية البحث في مواكبة التطورات في تصميم القباب باستخدام التصميم البارامتري وبرامج المحاكاة. يستخدم البحث المنهج التجريبي من خلال استخدام التصميم البارامتري والمؤشرات التصميمية للقباب، والتي أنتجت عددًا غير محدود من القباب، ولذلك يعتمد البحث على التحسين متعدد الأهداف لإيجاد أفضل الحلول القائمة على ثلاثة أهداف خاصة بالتصميم والأداء البيئي للقباب، ثم التحقق من الحلول المستخرج عن طريق حساب عامل ضوء النهار والراحة الحرارية التكيفية للوصول إلى الحل الأمثل. وقد توصلت الدراسة إلى مجموعة من النتائج: حيث قدمت النتائج مجموعة متنوعة من تصاميم القباب في ثلاث فئات محتلفة، وقد وصلت إلي معدلات جيدة للإضاءة الطبيعية وتراوحت الراحة الحرارية بها من 34٪ إلى 42%، بالإضافة الي وضع منهجية واضحة للقباب في مراحل التصميم الأولية تعتمد على مؤشرات للتصميم ومؤشرات ومعايير بيئية لتحقيق الحل الأمثل، كما ساعدت برامج المحاكاة في تطوير عملية تصميم القباب والوصول إلى نتائج دقيقة وموثوقة، كما إن تطوير المؤشرات التصميمية والبيئية للقباب سيساعد في تحقيق نتائج أفضل لتصميم القباب التي تحقق الراحة الحرارية والإضاءة الطبيعية.

الكلمات المفتاحية:

تصميم القبة، التحسين متعدد الأهداف، عامل ضوء النهار، الراحة الحرارية التكيفية، أدوات المحاكاة.

Glossary

Term	Definition
Parametric Design	The technique can create variations of design based on several factors during the initial design stage.
Generative design	The concept of producing complex shapes and patterns from a basic specification.
Natural Lighting	The lighting is generated naturally with the help of natural sources such as the sun.
Daylight Factor	The percentage of interior daylight illuminance on a given surface to simultaneously measure illuminance from an unobstructed overcast sky.
Thermal Comfort	An impression of mind that reflects satisfaction with the thermal environment.
Adaptive Thermal Comfort	A percentage expresses the relation between indoor and outdoor temperatures.
Simulation	A technique can examine and analyze the real world by creating a virtual World.
Simulation Tools	Tools used to simulate a real-life situation using models or interactive computer programs.
Multi-objective Optimization	A branch of optimization that addresses problems involving multiple conflicting objectives to find the optimal solution while considering multiple objective functions that must be simultaneously optimized.
Genetic algorithm	It chooses good-performing solutions from the current population and utilizes them as parents to generate the next generation, and the population "evolves" toward an ideal solution.

1. Introduction

Numerous paradigm changes have occurred in many different areas of knowledge throughout the last fifty years. This knowledge led to a rapid evolution in the design process using technological development. As a result of developments in technology and digital architecture, the design process developed and provided contemporary innovative designs and new forms by using parametric and generative design (Idi 2015, Lee 2010, Hadjadji, Toulan and Dorra 2023). The parametric design technique uses an algorithmic scheme to create dynamic, contemporary, innovative buildings (López-López, et al. 2023). In architecture, parametric design is modeling architectural geometry using parameters and functions. It has the flexibility of programming because it is more user-friendly than traditional programming languages due to its graphical user interface, visual codes, and ability to generate design alternatives quickly (Fang 2017). Generative design is utilizing the computer's virtual world by finding answers to complicated issues that are difficult to find using usual problem-solving methods (FRAZER, et al. 2002, Garber 2014, Zee and Vrie 2008, Bernal, Haymaker and Eastman 2015). Generative design uses computer power to address concerns of speed, accuracy, and complexity. It improves creativity by increasing the number of design variations, which include unexpected results that enhance the design process (Chaszar and Joyce 2016, ZHANG and XU 2018, Caetano, Santos and Leitão 2020).

In the last decade, increased research has applied generative design using evolutionary optimization to evaluate comfort considerations and energy performance for buildings in the initial design stage. Evolutionary optimization often uses a parametric building model, simulation tools, and algorithms to create an optimization problem. The parametric model makes several design options; simulation tools assess their performance according to performance criteria, and the optimization tool seeks the optimal design alternative. When an optimization problem has more than one objective, it is referred to as a multi-objective optimization problem, often used in architectural design research (Touloupaki and Theodosiou 2017, Liu, Wang and Ji 2022).

In 2020, Many studies dealt with the generative design of administrative, residential, and educational buildings with specific spaces. De Luca et al. discussed shading type and configuration for educational rooms to maximize the natural lighting (De Luca, Sepúlveda and Varjas 2022). Ferrara et al. (2018) and Futrell et al (2015). discussed room components as parameters to minimize the total energy. Taylor et al. studied indoor temperature, humidity, and airspeed to minimize energy costs and maximize thermal comfort (Taylor, Brown and Rim 2021). Zou et al. and Futrell reviewed room parameters like dimensions, shading devices, walls, and windows to maximize thermal comfort and natural lighting (Zou, Zhan and Xiang 2021, Futrell and Ozelkan 2014). Alkhatatbeh et al. discussed classroom parameters in different climate zones to maximize the natural lighting (Alkhatatbeh, Kurdi and Asadi 2023). These studies were evaluated based on the kind of building, design determinants, functional objectives of the optimization process, simulation programs for the environmental study of the building, and optimization tools for generative design, as shown in Figure 2.

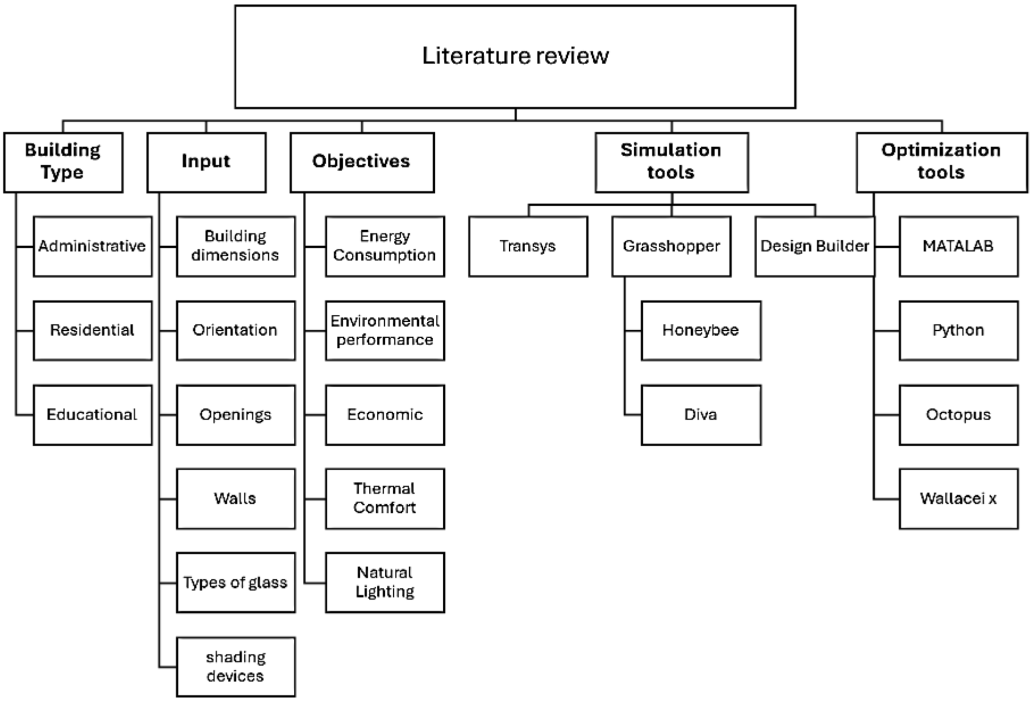


Figure 1 Literature review map

There is a huge deficit in studies related to buildings with wide spans, especially domes, and therefore the research is trying to link domes in contemporary architecture with parametric and generative design to preserve their environmental performance. According to the advancement of technology, more creative and attractive dome designs are expected, which will produce more significant, functional, and ecologically friendly spaces. The dome form is well-known as an architectural element that meets specific design requirements. Today's architects have designed domes to achieve new goals using contemporary construction technology. One of the significant benefits of modern construction technology is the ability to create large spaces without columns to reach large areas that were previously impossible (Yossef 2014).

Therefore, the research is trying to fill the gap by developing parametric and generative design in the dome's design, which provides environmental solutions. Despite the technological development and environmental solutions for domes, their environmental role was not adequately exploited. It was necessary to find a mechanism for dome designs compatible with the environment and provide environmental solutions to achieve thermal comfort for users and appropriate natural lighting.

1.1 Research Problem

The research problem is that parametric and generative design helped to achieve the variety and various shapes of domes. However, their environmental role throughout the design process may not be adequately investigated, and there is no practical method to study their thermal comfort and natural lighting to reach the most applicable shape of the dome. The research depends on the main hypothesis: "Modern simulation applications improve the environmental performance of buildings with wide spans, including domes." The research attempts to answer the following questions:

- How can contemporary applications be utilized in the design of domes to ensure optimal environmental performance?
- In what ways do parametric and generative design methodologies contribute to the development of dome shapes that maximize natural lighting and thermal comfort?
- Why modern technical applications are necessary for the design of domes in contemporary architecture?

1.2 Research objectives and importance

The primary purpose of the research is to develop a methodology for the design process of dome design to achieve thermal comfort and natural lighting. The research's importance is to keep up with the latest developments in designing domes using parametric and generative design and deducing different shapes. It can be applied in multiple buildings, such as cultural and entertainment facilities. It strengthens the environmental role of domes by achieving natural lighting and thermal comfort.

1.3 Research methodology

The research depends on the experimental method by modeling the geometric shape of the dome by using parametric design tools, optimizing the dome shape using generative design tools, and verifying the environmental role of the results by using environmental simulation tools to achieve an optimal solution for domes.

2. Contemporary Domes

Modern domes provide more technologies and applications in construction and structure techniques, which help to reach significant dimensions without supporting columns. They also offer new applications in environmental studies and achieve thermal comfort for users, like natural lighting and natural ventilation. The research discusses three examples of modern domes with various dimensions and sizes and technological development in design and environmental aspects and also used for entertainment and cultural uses. The three examples are the Reichstag Dome, the Millennium Dome, and the Louvre Abu Dhabi.

The Reichstag Dome: Foster and Partners designed the Reichstag Dome in Berlin in 1999. The dome's diameter is 40 meters, the height is 23.5 meters, and it stands on the roof of the Reichstag 24 m above ground, as shown in Figure 2. The dome has only one skin of steel ribs supported by a twin-helical steel ramp (Altin 2001). It consists of 24 catenary-shaped meridional ribs interconnected by 17 ring elements. The lantern ring at the dome top has a 9 m diameter (Roller and Sischka 1997). At the dome center is a "light air cone," which has a diameter of 2.5 m at its lower end, widening to 15 m at the level of the viewing platform, and is covered with 360 highly reflective glass mirrors. The dome utilizes natural light as an architectural feature and studies the sun's movement around the building and how this helped to bring light into the space, as shown in Figure 3. The cone is associated with a moveable sun shield blocking solar gain and glare during the day (Schulz, Foster and Thierse 2000). The light air cone is a part of the ventilation system, directing air toward the dome's top. The cone is associated with a moveable sun shield that blocks solar gain and daytime glare (Nastarani, Khaksari and Mohammadi 2017).

Figure 2 The Reichstag Dome
Source: (Schulz, Foster and Thierse 2000)

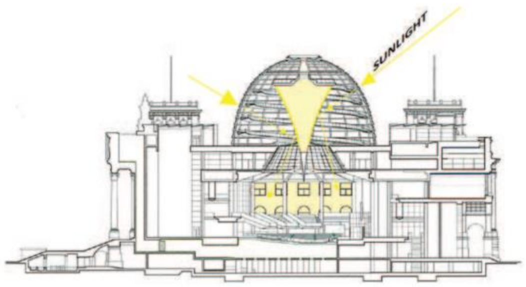


Figure 3 Natural Lighting in the Reichstag dome
Source: http://www.karinazarzar.com

The Millennium Dome: Richard Rogers designed the Millennium Dome in Greenwich, London, to mark the birth of the 21st century in 1999, as shown in Figure 4. The dome covers 100,000 m^2 and is 365 meters in diameter. The dome has a maximum height of 50 meters, above which twelve masts reach a height of 100 meters, supporting the fabric with more than 70 kilometers of high-strength steel cable (Brink 2019). The dome consists of a central cable ring and edge cable anchored to the ground between 72 radially distributed tensioned steel stringer cables and connected to the twelve masts, which helped to create a very efficient self-balancing structure. The engineering service team envisaged the dome as an umbrella, which visitors would enter dressed according to the external climate. The aim is a tempered environment, as shown in Figure 5 The dome's translucent fabric allows sunlight to penetrate, decreasing the requirement for internal lighting and the building's energy demands (Yossef 2014). The dome is also naturally ventilated, with openings in the roof's center expelling rising hot air and twelve fans pulling cold air inside the dome.

Figure 4 The Millennium Dome
Source:
https://www.burohappold.com/projects/millennium-dome/#

Figure 5 The dome as an umbrella
Source:
https://www.burohappold.com/projects/millennium-dome/#

Louvre Abu Dhabi: Jean Nouvel designed the Louvre on Saadiyat Island, Abu Dhabi, in 2017, as shown in Figure 6. Jean Nouvel inspired the Louvre Abu Dhabi concept from traditional Arabic architectural culture (Nouvel 2017). A large dome, 180 meters in diameter, envelops most of the museum city. The dome comprises eight layers: four inner layers clad in aluminum and four outer layers clad in stainless steel, separated by a five-meter-high steel frame. The number of 'stars' that form the dome's eight cladding layers is 7,850. The dome stands on only four permanent piers, each 110 meters apart. The interior dome elevation from the ground floor to the cladding is 29 m, and the highest point of the dome above sea level is 40 m. (Imbert, et al. 2013). The Louvre Abu Dhabi benefits from natural lighting. When the sun's rays illuminate it, they filter the light, creating a striking effect known as “a rain of light” under the dome to achieve 300 lux of light inside the project as shown in Figure 7. This phenomenon is now associated with Abu Dhabi's Louvre eight-layered dome, made from complex geometric structures floating above an inner space (Musfy, Sosa and Ahmad 2021). The dome can reduce cooling costs by 25% and reduce heat gain by 42% (Nouvel 2017).

Figure 6 The Louvre Abu Dhabi Dome
Source:
https://www.archdaily.com/883157/louvre-abu-dhabi-atelier-jean-nouvel

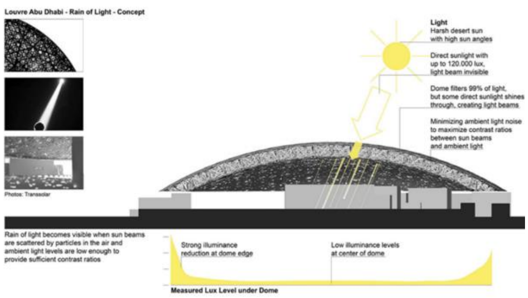


Figure 7 The natural lighting
Source: https://transsolar.com/projects/louvre-abu-dhabi

The three domes can be compared by a combination of elements as shown in Table 1. The domes' diameters range from 40 to 360 M, the heights range from 23.5 to 50 M, and the domes consist of horizontal and vertical ribs ranging from 17 to 72 ribs, in addition to the role of these domes in achieving thermal comfort and natural lighting.

TABLE 1 COMPARISON OF THE THREE EXAMPLES

	Function	The dome nature	Dome type	Dimensions	The dome structure	The dome Environmental
The Reichstag dome	Cultural and entertaining	Attached to the building	Hemispherical dome	The diameter is 40 m. The height is 23.5 m.	24 catenary-shaped meridional ribs, 17 ring, a circular opening diameter of 9 m, and a 1.6-meter clear-width helical ramp, and a "light air cone"	The dome allows natural ventilation and daylight into the space. The building depends on optimizing passive systems while minimizing active systems.
Millennium Dome	Entertaining	Freestanding	Cable net dome	The diameter is 365 m. The height is 50 m.	Twelve masts reach 100 meters, supporting it with 72 radially distributed tensioned steel stringer cables.	The dome design was with great care taken to minimize the environmental impact of the building.

Louvre Abu Dhabi	Cultural	Freestanding	Braced dome	The dome's diameter is 180 m The height is 40 m.	Eight layers, four inner layers clad in aluminum and four outer layers clad in stainless steel, a five-meter-high steel frame. The dome stands on four permanent piers, each 110 meters apart.	The dome protects the buildings and outdoor plaza from the sun's heat, improves visitors' comfort, and reduces building energy consumption.

3. Design indicators for domes

According to the study of contemporary domes, The domes were classified into three primary categories to achieve diversity in use according to the size and shape of the dome. The domes were also classified based on their design indicators, although the structural system and material remained constant: small, medium, and large domes.

- The small dome: The diameter ranges from 24 to 120 meters, the height from 12 to 60 meters, the number of horizontal and vertical ribs from 12 to 60, and the Oculus opening from 0 to 15 meters.
- The medium dome: The diameter ranges from 120 to 240 meters, the height from 12 to 60 meters, the number of horizontal and vertical ribs from 12 to 60, and the Oculus opening from 0 to 30 meters.
- The large dome: The diameter ranges from 240 to 360 meters, the height from 12 to 60 meters, the number of horizontal and vertical ribs from 12 to 72, and the Oculus opening from 0 to 45 meters.

4. Research methods

The research focused on the Greater Cairo climatic zone, which is the prevalent climate in Egypt and the Middle East because most of the buildings in the region have a traditional style and depend on domes. Therefore, the research used the Cairo International Airport verified weather file (30.122N, 31.406E).

The research independently identified each category of the dome using the parametric design, indicators, and parameters of dome design, which produced an unlimited number of domes in each category. Therefore, it was necessary to set three objectives to reach the best solution using a multi-objective genetic algorithm, including the lowest percentage of incident solar radiation inside the dome, the most significant external surface area of the dome, and Oculus to achieve the maximum amount of natural lighting, Then, the tool helped to select the best solutions based on the most repeated solutions with the most minor incident solar radiation inside the dome. The extracted solutions' natural lighting and thermal comfort were calculated to verify the results to reach the optimal solution for each category, as shown in Figure 8.

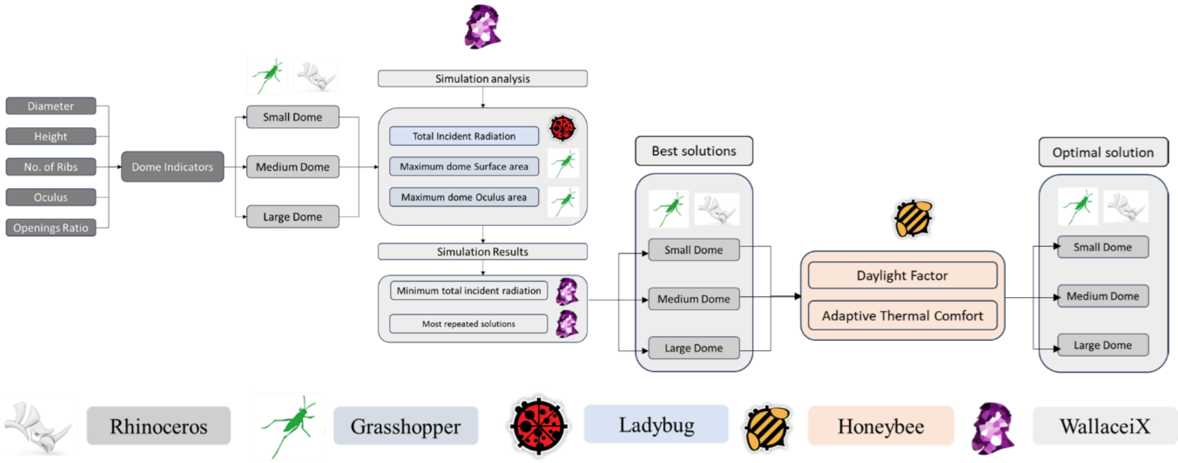


FIGURE 8 THE RESEARCH WORKFLOW
SOURCE: RESEARCHERS

4.1 Parametric Model

The research used Rhino and Grasshopper to organize each category of domes in a file based on the design indicators and determinants. The research used the parametric tool called Rhinoceros, usually known as Rhino or Rhino3D (--, Rhino - Rhinoceros 3D n.d.), a 3D computer-aided design (CAD) tool. Rhino and Grasshopper are used as free-form NURBS (Non-Uniform Rational Basis Spline) modelers (---, Grasshopper3D n.d.). Rhino is often used for parametric design in conceptual design phases as an efficient method to build and assess alternative design concepts. Developer plugins in Rhino and Grasshopper will allow Rhino models to be fully interoperable throughout the design process (Braasch 2016).

4.2 Incident Solar Radiation Model

The research depends on Environmental Simulation Tools (ESTs) like Ladybug (-- n.d.). Ladybug is a plugin composed of components that analyze weather data within Grasshopper, specifically standard EnergyPlus weather files (.EPW). It generates a range of 3D interactive visualizations displayed in Rhino to aid decision-making during the design process. Ladybug tool used to model and calculate Incident solar radiation[1], which can directly affect indoor thermal comfort. Furthermore, it can increase the outside surface temperature of the building, which affects indoor thermal comfort and increases cooling and heating loads. It is the main factor in heat gain in buildings. Moreover, solar radiation is responsible for daylighting, which can be beneficial to building energy conservation and a comfortable indoor environment. A better understanding of solar radiation will lead to successful building design (An, et al. 2020)

4.3 Generative Design Analysis

The research depends on the genetic algorithm, the most popular optimization algorithm in building performance studies. The genetic algorithm randomly chooses good-performing solutions from the current population and utilizes them as parents to generate the next generation, and the population "evolves" toward an ideal solution (Nguyen, Reiter and Rigo 2014). WallaceiX version 2.7 (n.d.) is a Grasshopper-based evolutionary engine that allows users to run evolutionary simulations. It provides several alternatives for defining the design challenge, examining the outputted findings, and picking solutions. WallaceiX uses the multi-objective evolutionary algorithm as it is primarily an evolutionary algorithm and promotes non-dominated solutions while maintaining diversity, i.e., A population's elites are passed on to the following generation. The solver component requires two sets of inputs: variables (Genes) and fitness objectives (FO) (Makki, Showkatbakhsh and Song 2019). After studying the inputs that affect the design of domes(Genes), the research used The WallaceiX tool. It determined three goals(FO): minimizing the solar radiation incident inside the dome by using the Ladybug tool, maximizing the area of the dome's outer surface for natural lighting, and maximizing the dome Oculus. The WallaceiX tool performs a simulation of inputs to reach the objectives. As any change in the range of the input numbers will directly affect the objectives, the tool determines the sample number. It performs the changes to reach the most appropriate solutions for the objectives and helps choose the best solutions, as shown in Figure 9.

The simulation occurred on the 11th Gen Intel (R) Core (TM) i7-11800H @ 2.30GHz Processor. An experimental simulation of domes was conducted using the default sample size specified in the program, which was a 2000 sample consisting of 100 generations, and each generation counted 200 samples. After performing the experimental simulation, it was noted that after the sample of 600, the same results were repeated. According to that, the research determined the sample size to be 600 samples consisting of 30 generations, and each generation counted 20 samples for all the following experiments. The simulation was carried out on each category of domes separately, and 600 samples were derived for the small dome from 3.6e16, as shown in Figure 10, for the medium dome from 9e16, as shown in Figure 11, and for the large dome from 2.1e17, as shown in Figure 12.

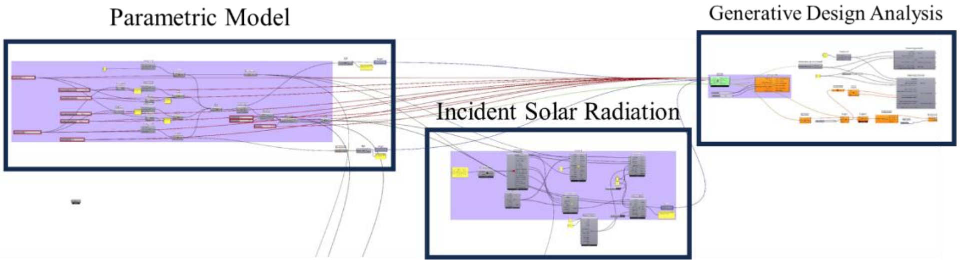


FIGURE 9 PREPARING GENERATIVE DESIGN ANALYSIS FOR THREE CATEGORIES OF DOMES

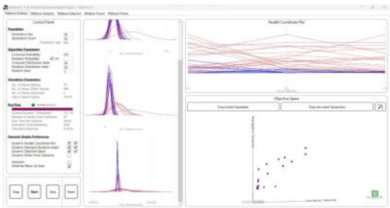


Figure 10 WallaceiX Simulation for the small dome

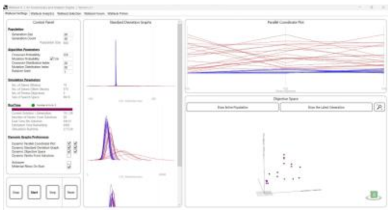


Figure 11 WallaceiX Simulation for the medium dome

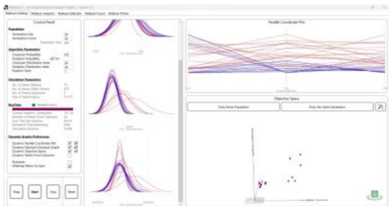


Figure 12 WallaceiX Simulation for the large dome

4.4 The process of selection

After conducting the simulation, The WallaceiX program also helped select the best solutions from 600 samples that match the objectives. There are 6 to 7 shapes chosen for each category of domes with the minimum solar radiation, in addition to the repetition rate of selected domes with the minimum incident solar radiation, reaching up to 10% of the total sample.

4.5 Thermal analysis

The research depends also on the Honeybee tool (---, Honeybee n.d.). Honeybee is a plugin that connects Grasshopper with EnergyPlus, Radiance, and OpenStudio to simulate building energy, thermal, and daylight. The outputs from Ladybug's components are frequently used in Honeybee to provide more informed analysis. Ladybug and Honeybee use Grasshopper's flexible, component-based visual programming interface to connect environmental data sets and simulation engines dynamically. (Sadeghipour Roudsari and Pak 2013)

The research focuses on natural lighting, which aids in sufficient illumination of visual tasks, creating an appealing visual environment, conserving electrical energy, and providing light for our biological needs (VELUX 2014). There is enough evidence in the literature to indicate that illuminances in the 100 to 3000 lux range will likely reduce electric lighting usage significantly. It also provides the amount of illuminance required for a specific visual task (Mardaljevic, et al. 2012). A simulation was conducted to calculate the daylight factor, described as the percentage of interior daylight illuminance on a given surface to simultaneously measure illuminance from an unobstructed overcast sky. The higher the DF, the more daylight in the room (Tregenza and Wilson 2011). A daylight factor of 2% or above is considered daylit, and electric lighting may still be required. When the average Daylight Factor reaches 5% or more, a space may appear significantly daylit; however, visual and thermal conditions may be unsuitable (CIBSE 2002).

The research studies thermal comfort[2], which is necessary to help designers provide users with a thermally comfortable indoor environment. According to thermal comfort research, temperature, geographical location, and the built environment influence thermal comfort for users inside the building (Lamsal, Bajracharya and Rijal 2023). A simulation was conducted to calculate adaptive thermal comfort, expressed by a percentage. It depends on the relation between indoor design and outdoor temperatures. Adaptive thermal comfort understands that users can adapt to, or even prefer, a more comprehensive range of conditions. It investigates how people interact with their thermal surroundings. The adaptable technique, particularly in free-running buildings, enables building designers to forecast the internal temperature that provides comfortable conditions for the occupants (Nicol and Humphreys 2002). A simulation was conducted to calculate each dome's daylight factor and adaptive thermal comfort, as shown in Figure 13. The results are used to reach the optimum environmental dome based on the design and environmental indicators.

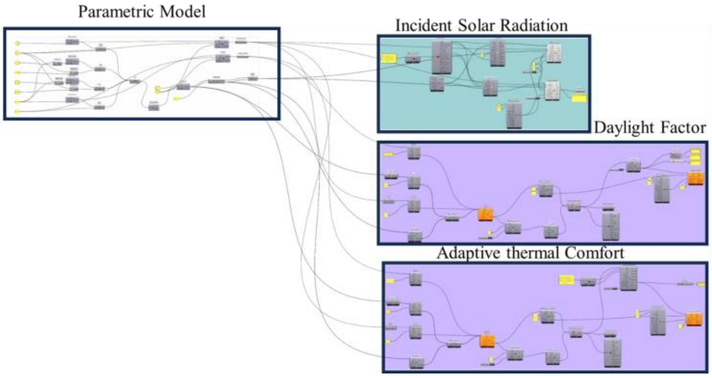


Figure 13 The Daylight factor and adaptive thermal comfort simulation.

4.6 Optimal Solution

A simulation was conducted to calculate incident solar radiation Kwh/m2, daylight factor as a percentage, and adaptive thermal comfort as a percentage. The simulation provided a shape representing the incident solar radiation inside the dome within a color range; Blue indicates low solar radiation rates, and red indicates high solar radiation rates. The simulation also generates a shape expressing the daylight factor percentage with a color range. The closer-to-blue color indicates an acceptable percentage of natural light, whereas the closer-to-red color indicates an unacceptable rate of natural light. In contrast, the simulation generates a shape that shows the percentage of adaptive thermal comfort within the color range; Red indicates a high percentage of adaptive thermal comfort, while blue indicates a low rate of adaptive thermal comfort. This simulation helped in choosing the optimal solution.

4.7 Validation of tools

An environmental simulation of the Louvre dome was carried out and the simulation results were compared with the results of published measurements. The researchers modeled the dome on the Rhino and Grasshopper programs according to the drawings and dimensions of the dome of the Louvre Museum in Abu Dhabi as shown in Figure 14, and then converted it to a thermal model using Ladybug and Honey Bee software to make an environmental simulation of the dome. An environmental simulation was conducted and the results of the daylight factor were extracted.

Comparing the results published in the journal Advances in Architectural Geometry (Imbert, et al. 2013), the measurements found that the illumination intensity below the dome ranges from 100 to 300 lux, representing from 1 to 3% of the daylight factor, and the simulation results showed that the average daylight factor throughout the year is 3.4%, as shown in Figure 15. It explains the high accuracy of the computer programs employed in the modeling procedure because the findings were almost identical to published measurements.

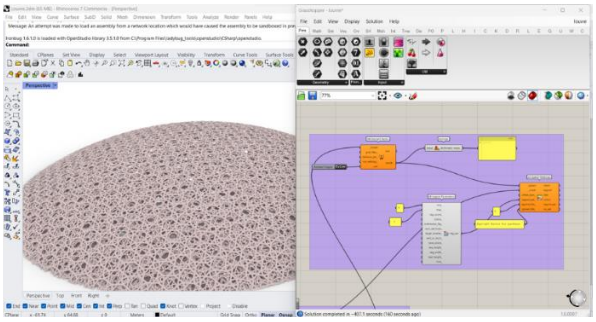


Figure 14 Louvre Abu Dhabi modelling

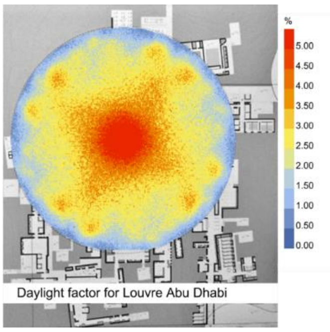


Figure 15 The Daylight factor of Louvre Abu Dhabi

5. Results

5.1 Small dome

Six domes in the small category matched the two selection factors. The selected domes were from the 29-generation samples no. 1, 9, and 13, the 6-generation sample no. 15, the 12-generation sample no. 19, the 15-generation sample no. 3, indicated by the dome Oculus area (FV. 1), outer surface area (FV. 2), and incident solar radiation (FV. 3), as shown in Figure 16.

Figure 16 The six domes chosen for the small dome.

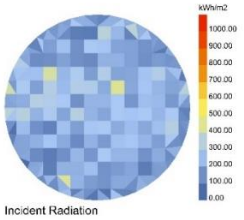
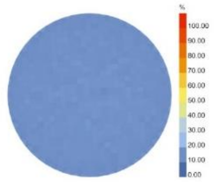
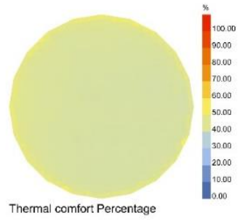
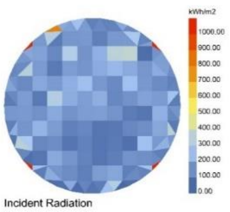
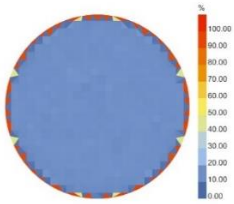
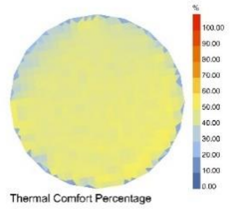
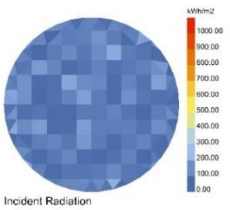
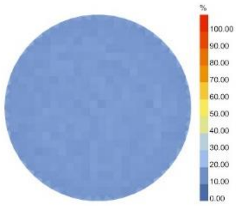
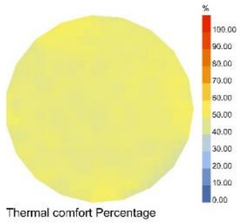
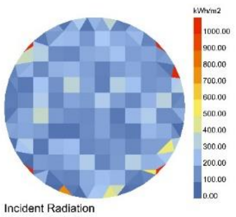
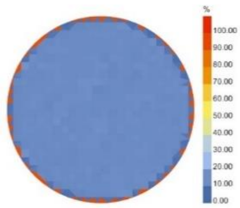
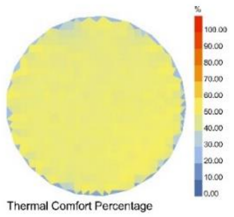
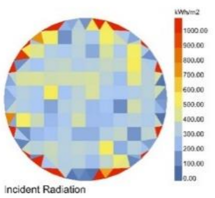
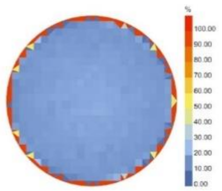
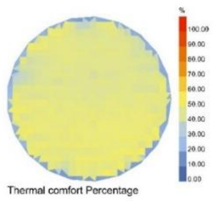
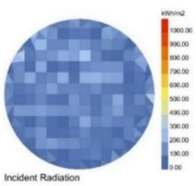
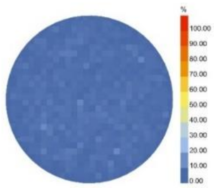
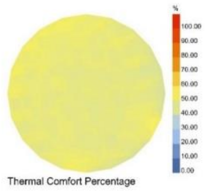
The design indicators, repetition rate, and incident solar radiation have been extracted for each selected dome, as shown in Table 2. The table shows that dome No.1 has the highest repeat rate in the sample by 16 times, while the fifth and sixth domes have the lowest repeat rate by 9 times. The table also reveals that dome No.3 has the lowest rate of total incident solar radiation throughout the year, at 24338.6 Kwh, followed by dome No.6 at an average of 46413.05 Kwh, followed by dome No.2 at an average of 57259.47 Kwh. The results also showed that the best diameter for the small dome is 24 and 28m, the height ranged from 12 to 30m, the oculus diameter ranged from 0.2 to 5.8 m, and the ratio of opening ranged from 41 to 46%.

TABLE 2 THE RESULTS OF THE SIX SELECTED SMALL DOMES

Category	Diameter m	Height m	Ribs		Oculus Diameter m	Ratio of Openings %	Number of repetitions	Incident Radiation kWh	Dome Shape
			Horizontal	vertical					
Small dome 1	28	20	27	56	4.8	42	16	104658.17	
Small dome 2	24	14	22	58	0.4	43	12	57259.47	
Small dome 3	24	32	27	54	0.2	46	12	24338.6	
Small dome 4	24	19	30	59	0.2	41	11	69799.07	
Small dome 5	24	12	30	59	5.8	45	9	154692.07	
Small dome 6	28	29	27	57	3.6	45	9	46413.05	

The results of the thermal analysis are the daylight factor and adaptive thermal comfort for the small dome category, as shown in Table 3.

TABLE 3 THE RESULTS OF THE DAYLIGHT FACTOR AND ADAPTIVE THERMAL COMFORT FOR SIX SELECTED SMALL DOMES

Category	Total Solar radiation	Daylight factor %	Adaptive Thermal Comfort %
	104658.17	10.69%	42.1%
Small dome 1			
	57259.47	19.22 %	38.21%
Small dome 2			
	24338.6	12.77%	42.398%
Small dome 3			
	69799.07	17.1%	39.62%
Small dome 4			
	154692.07	28.74%	36.13%
Small dome 5			
	46413.05	12.29%	42.05%
Small dome 6			

The optimal solution for the small category showed that:

- The natural lighting simulation of the selected domes in the small dome category shows that small dome No. 1 has the best daylight factor between others of 10.69%, followed by small dome No. 6 with a percentage of 12.29%, followed by small dome No. 3 with a percentage of 12.77%. The results of daylight factor are close to 5%, indicating that the space is well-daylit, but if the rate of daylight factor increases above 5%, visual and thermal conditions appear.

- The thermal comfort findings of the small domes indicate that thermal comfort for domes ranged from 36% to 42%, with dome No. 3 coming in first with 42.4%, followed by dome No. 1 with 42.1%, and dome No. 6 with 42.05%.

It is clear from the results of the analysis that the three best domes in the category of small domes are small dome No. 1, small dome No. 3, and small dome No. 6 due to the proximity of the results of the daylight factor to 5% and the high thermal comfort rates among the rest of the domes to 42%, as shown in Figure 17.

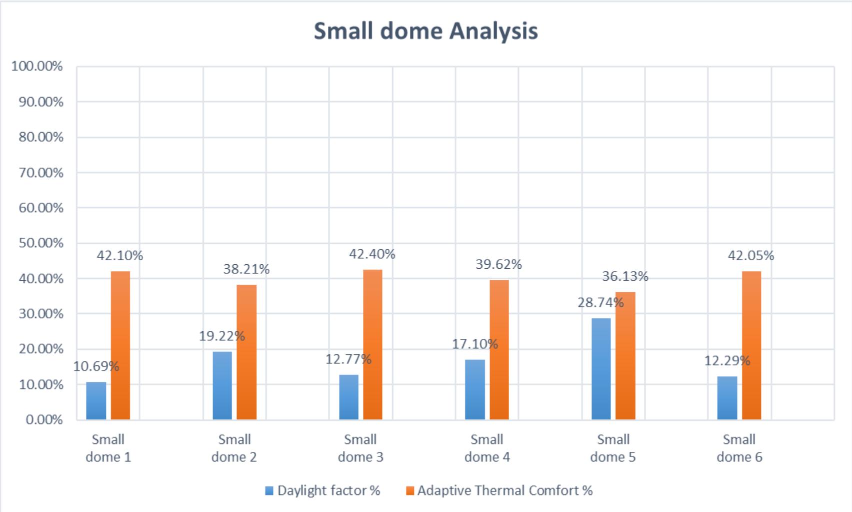


Figure 17 The result of natural lighting and thermal comfort for the small dome.

From the results of the small dome, it is clear that the closer the value of the daylight factor to the favorable rates, the higher the value of thermal comfort inside the dome, The dome shape and the ratio of openings are some of the main elements that affect the value of the daylight factor, and It was also determined that the higher the height, the better the thermal comfort ratio within the dome.

5.2 Medium dome

Seven domes in the medium category matched the two selection factors. The selected domes were from the 29-generation sample no. 4, the 12-generation sample no. 6, the 4-generation sample no. 13, the 15-generation sample no. 14, the 19-generation sample no. 7, the 21-generation sample no. 15, the 24-generation sample no. 10 indicated by the dome Oculus area (FV. 1), outer surface area (FV. 2), and incident solar radiation (FV. 3), as shown in Figure 18.

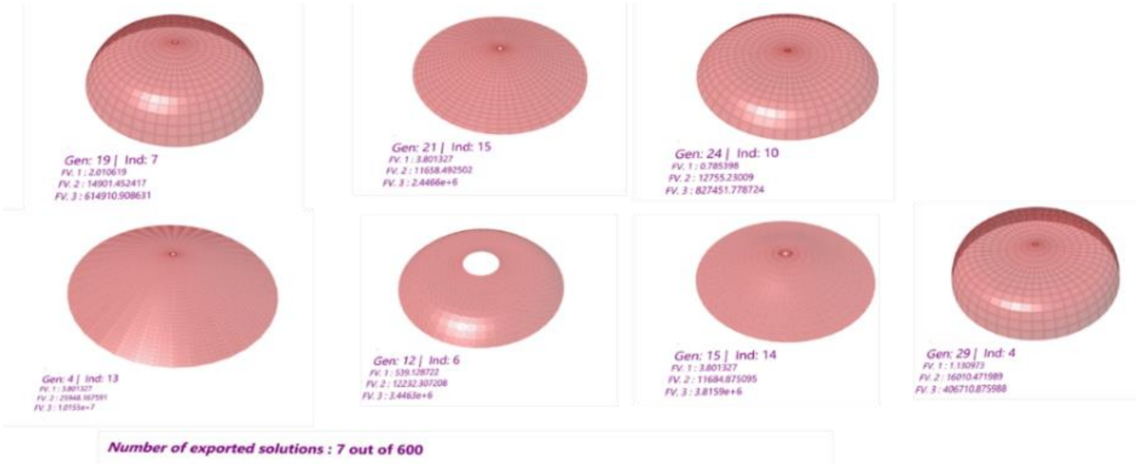


Figure 18 The seven domes chosen for the medium dome.

The design indicators, repetition rate, and incident solar radiation have been extracted for each selected dome, as shown in Table 4. The table shows that dome No.1 has the highest repeat rate in the sample by 9 times, and from the third to the seventh dome has the lowest repeat rate by 7 times. The table also reveals that dome No.1 has the lowest rate of total incident solar radiation throughout the year, at 406710.9 Kwh, followed by the dome No. 5 at an average of 614910.9 Kwh, followed by dome No.7 at an average of 827451.8Kwh. The results also showed that the best diameter for the medium dome is 120, 122, and 176 m, the height ranged from 13 to 27m, the oculus diameter ranged from 1.2 to 26.2 m, and the ratio of opening ranged from 32 to 90%.

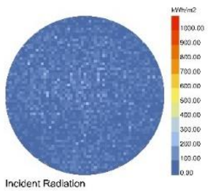
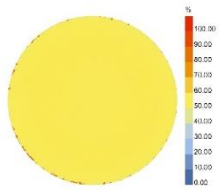
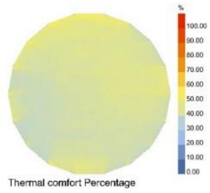
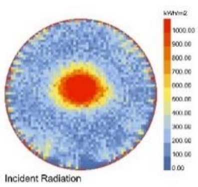
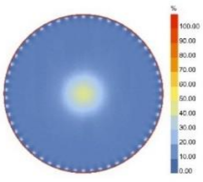
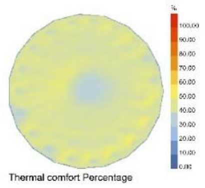
TABLE 4 THE RESULTS OF THE SEVEN SELECTED MEDIUM DOMES

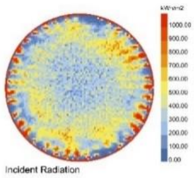
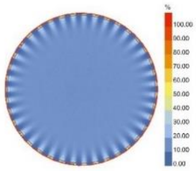
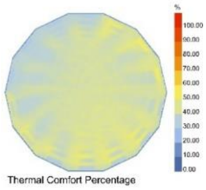
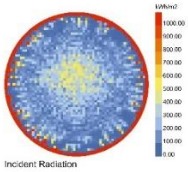
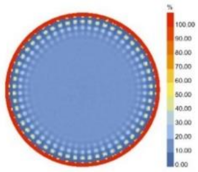
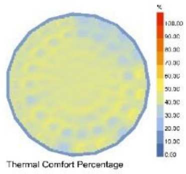
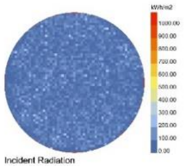
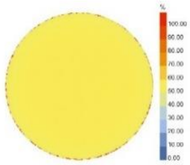
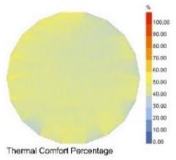
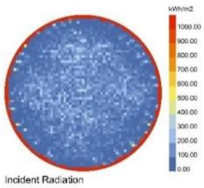
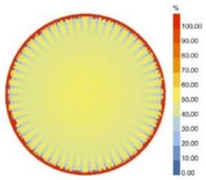
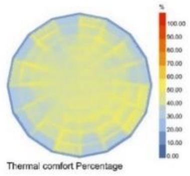
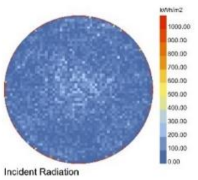
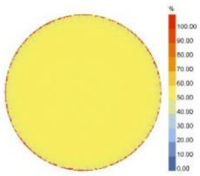
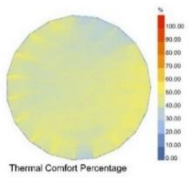
Category	Diameter m	Height m	Ribs Horizontal	Ribs vertical	Oculus Diameter m	Ratio of Openings %	Number of repetitions	Incident Radiation kWh	Dome Shape
Medium dome 1	120	22	14	51	1.2	90	9	406710.9	
Medium dome 2	122	13	12	54	26.2	32	8	3446300	
Medium dome 3	176	27	30	39	2.2	45	7	10155000	

Category	Diameter m	Height m	Ribs Horizontal	Ribs vertical	Oculus Diameter m	Ratio of Openings %	Number of repetitions	Incident Radiation kWh	Dome Shape
Medium dome 4	120	13	13	54	2.2	46	7	3815900	
Medium dome 5	120	26	14	52	1.6	89	7	614910.9	
Medium dome 6	120	13	20	54	2.2	83	7	2446600	
Medium dome 7	120	13	13	54	1	87	7	827451.8	

The results of daylight factor and adaptive thermal comfort for the medium dome category, as shown in Table 5

TABLE 5 THE RESULTS OF THE DAYLIGHT FACTOR AND ADAPTIVE THERMAL COMFORT FOR SEVEN SELECTED MEDIUM DOMES

Category	Total Solar radiation	Daylight factor %	Adaptive Thermal Comfort %
Medium dome 1	406710.9 	51.67% 	38.17% 
Medium dome 2	3446300 	13.55% 	36.99% 
	10155000	16.42%	35.69%

Category	Total Solar radiation	Daylight factor %	Adaptive Thermal Comfort %
Medium dome 3			
	3815900	23.57%	34.73%
Medium dome 4			
	614910.9	50.96%	38.69%
Medium dome 5			
	2446600	47.50%	34.96%
Medium dome 6			
	827451.8	48.87 %	37.35%
Medium dome 7			

The optimal solution for the medium category showed that:

- The natural lighting simulation of the selected domes in the medium dome category shows that medium dome No. 2 has the best daylight factor among others at 13.55%, followed by medium dome No. 3 with a percentage of 16.42%, followed by medium dome No. 4 with a percentage of 23.57%. The results of daylight factor are close to 5%, indicating that the space is well-daylit, but if the rate of daylight factor increases above 5%, visual and thermal conditions appear.

- The thermal comfort findings of the medium domes indicate that thermal comfort for domes ranged from 34% to 38%, with dome No. 5 coming in first with 38.69%, followed by dome No. 1 with 38.17%, and dome No. 7 with 37.35%.

It is clear from the results of the analysis that the three best domes in the category of medium domes are medium dome No. 2, medium dome No. 3, and medium dome No. 4 due to the proximity of the results of the daylight factor to 5% and the thermal comfort rates are approaching the highest thermal comfort rates in the seven domes, and the difference from the highest rates is only about 3%, as shown in Figure 19.

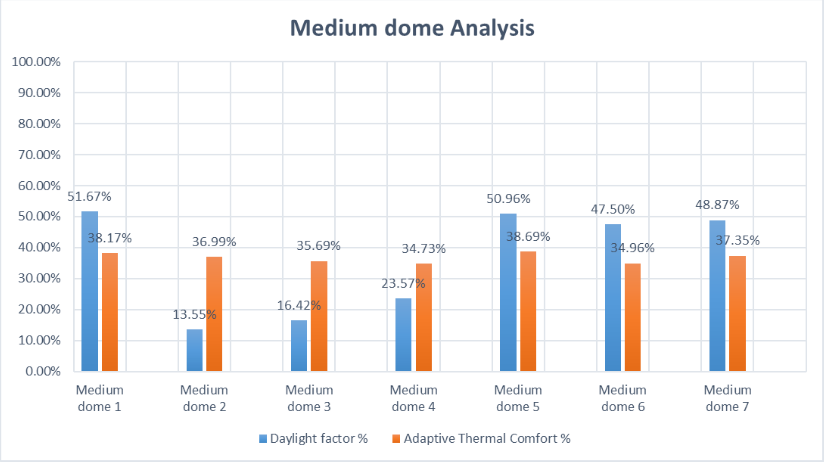


Figure 19 The result of natural lighting and thermal comfort for the medium dome.

From the results of the medium dome, it is clear that the closer the value of the daylight factor to the favorable rates, the higher the value of thermal comfort inside the dome, The ratio of openings, the height, and the Oculus diameter are the main element that affects the value of the daylight factor and the thermal comfort ratio in the medium dome.

5.3 Large dome

Seven domes in a large category matched the two selection factors. The selected domes were from the 29-generation samples no. 1, 9, 12, and 18, the 26-generation sample no. 12, the 16-generation sample no. 17, the 23-generation sample no. 5, indicated by the dome Oculus area (FV. 1), outer surface area (FV. 2), and incident solar radiation (FV. 3), as shown in Figure 20.

Figure 20 The seven domes chosen for the large dome.

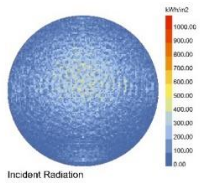
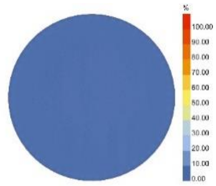
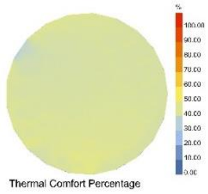
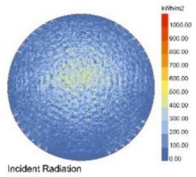
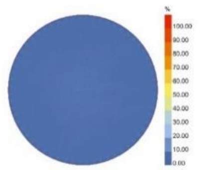
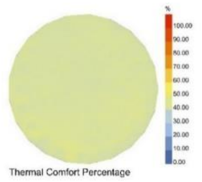
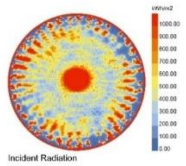
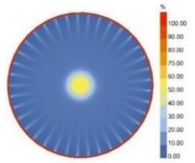
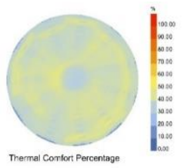
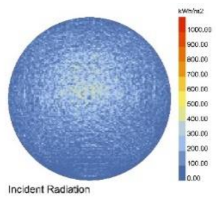
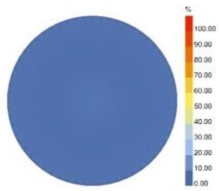
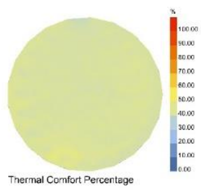
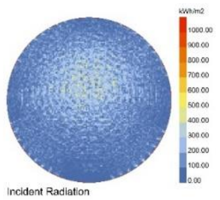
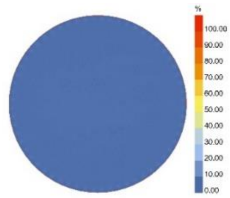
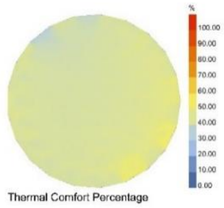
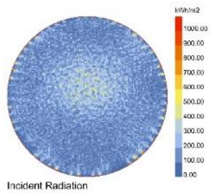
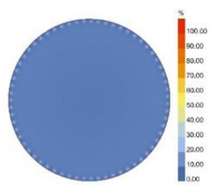
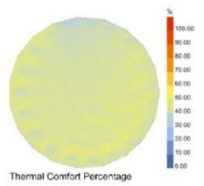
The design indicators, repetition rate, and incident solar radiation have been extracted for each selected dome, as shown in Table 6. The table shows that dome No.1 has the highest repeat rate in the sample by 15 times, while dome No.7 has the lowest repetition rate by 1 time. The table also reveals that dome No.7 has the lowest rate of total incident solar radiation throughout the year, at 4613700 Kwh, followed by the dome No.4 at an average of 4801400 Kwh, followed by the dome No.1 at an average of 827451.8Kwh. The results also showed that the best diameter for the large dome is 240 and 242 m, the height ranged from 12 to 59m, the oculus diameter ranged from 2.2 to 41.8 m, and the ratio of opening ranged from 17 to 33%.

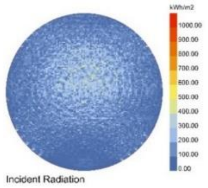
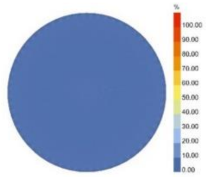
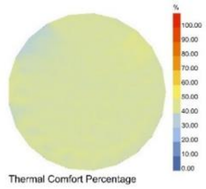
TABLE 6 THE RESULTS OF THE SEVEN SELECTED LARGE DOMES

Category	Diameter m	Height m	Ribs Horizontal	Ribs vertical	Oculus Diameter m	Ratio of Openings %	Number of repetitions	Incident Radiation kWh	Dome Shape
Large dome 1	242	59	14	61	3.8	17	15	5014900	
Large dome 2	242	57	13	60	15.2	17	13	5630000	
Large dome 3	242	12	34	37	41.8	22	12	24259000	
Large dome 4	242	58	14	60	16.6	22	12	4801400	
Large dome 5	242	59	14	60	2.2	17	12	5064300	
Large dome 6	240	56	17	63	0.4	33	10	6184500	
Large dome 7	242	58	14	60	13.4	22	1	4613700	

The results of daylight factor and adaptive thermal comfort for the large dome category, as shown in Table 7

TABLE 7 THE RESULTS OF THE DAYLIGHT FACTOR AND ADAPTIVE THERMAL COMFORT FOR SEVEN SELECTED LARGE DOMES

Category	Total Solar radiation	Daylight factor %	Adaptive Thermal Comfort %
	5014900	2.4 %	38.29%
Large dome 1			
	5630000	3.38%	38.2%
Large dome 2			
	24259000	10.7 %	34.156%
Large dome 3			
	4801400	2.875%	38.41%
Large dome 4			
	5064300	3.03%	38.34%
Large dome 5			
	6184500	7.13%	38.16%
Large dome 6			
	4613700	2.976 %	37.65%

Category	Total Solar radiation	Daylight factor %	Adaptive Thermal Comfort %
Large dome 7			

The optimal solution for the medium category showed that:

- The natural lighting simulation of the selected domes in the large dome category shows that large dome No. 2 has the best daylight factor among others at 3.38%, followed by large dome No. 5 with a percentage of 3.03%, followed by large dome No. 7 with a percentage of 2.976%. The results are close to 5%, indicating that the space has comfortable rates of natural lighting, and because the rate of daylight factor is less than 5%, there are no visual and thermal unsuitable conditions.

- The thermal comfort findings of the large domes indicate that thermal comfort for domes ranged from 34% to 38%, with dome No. 4 coming in first with 38.41%, followed by dome No. 5 with 38.34%, and dome No. 1 with 38.29%.

It is clear from the analysis results that the three best domes in the category of large domes are large dome No. 2, large dome No. 5, and large dome No. 7 due to the proximity of the results of the daylight factor to 5% and the thermal comfort rates are approaching the highest thermal comfort rates in the seven domes, and the difference from the highest rates is only about 1%, as shown in Figure 21.

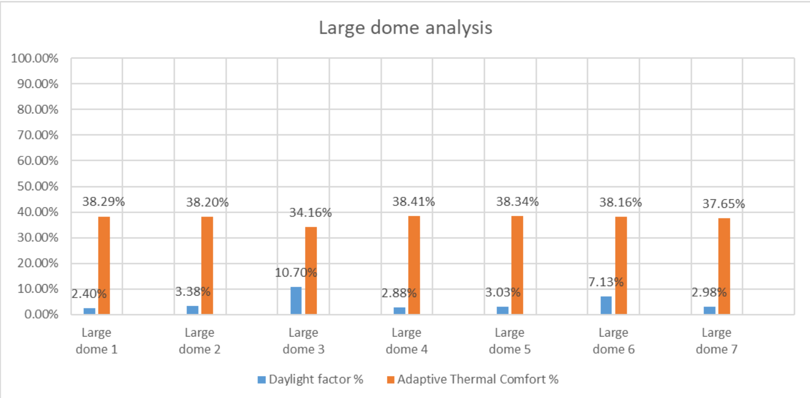


Figure 21 The natural lighting and thermal comfort result for the large dome.

From the results of the large dome, it is clear that the closer the value of the daylight factor to the favorable rates, the higher the value of thermal comfort inside the dome, It was determined that the higher the height, the better the thermal comfort ratio within the dome, and When the diameter of the large dome increases and the ratio of openings decreases, the higher the rates of good natural lighting and the higher thermal comfort.

5.4 Comparison of the three categories

It is clear from the comparison that the sizes of domes in the three categories that achieve good rates of natural lighting and thermal comfort are as follows:

- Small dome: The diameter ranges from 24 to 28 meters, the height from 12 to 32 meters, the number of horizontal and vertical ribs from 22 to 59, the Oculus opening from 0.2 to 5.8 meters, and the ratio of opinings from 41 to 46%.
- Medium dome: The diameter ranges from 120 to 176 meters, the height from 13 to 27 meters, the number of horizontal and vertical ribs from 12 to 54, the Oculus opening from 1.2 to 26.2 meters, and the ratio of opinings from 32 to 90%.
- Large dome: The diameter ranges from 240 to 242 meters, the height from 12 to 59 meters, the number of horizontal and vertical ribs from 13 to 64, the Oculus opening from 0.4 to 41.8 meters, and the ratio of opinings from 17 to 33%.

It has been shown from the results of the three categories that the closer the daylight factor to the preferred rates, the greater the thermal comfort ratio, and the height, the ratio of openings, and the oculus diameter are factors affecting thermal comfort and natural lighting.

6. Discussion

The research provides a new vision for the design of domes using parametric and generative design, which helps to produce a variety of shapes for domes based on design and environmental indicators. The research presents a clear methodology for designing contemporary domes in the initial stages to reach the optimum solutions for domes to achieve suitable natural lighting and thermal comfort for users inside the dome, as shown in Figure 22. The methodology depends on a set of elements as follows:

1. The first step is to determine the dome size and area from the three categories of domes and apply the design indicators for this category: the dome diameter, height, number of horizontal and vertical ribs, the oculus, and the ratio of openings.
2. The second step is determining the dome's location and studying the surrounding climatic conditions.
3. The third step is using parametric design for designing the dome based on design indicators and using generative design with a set of environmental and design objectives to conduct a simulation to reach a group of the best dome designs.
4. If the experiment does not provide the intended results, the experiment is repeated by modifying or adding design and environmental indicators.
5. The fourth step is to verify the results by conducting an environmental simulation for the extracted domes from the previous step by calculating the natural lighting and thermal comfort inside each dome.
6. The fifth step is to choose the best design solutions for the dome.

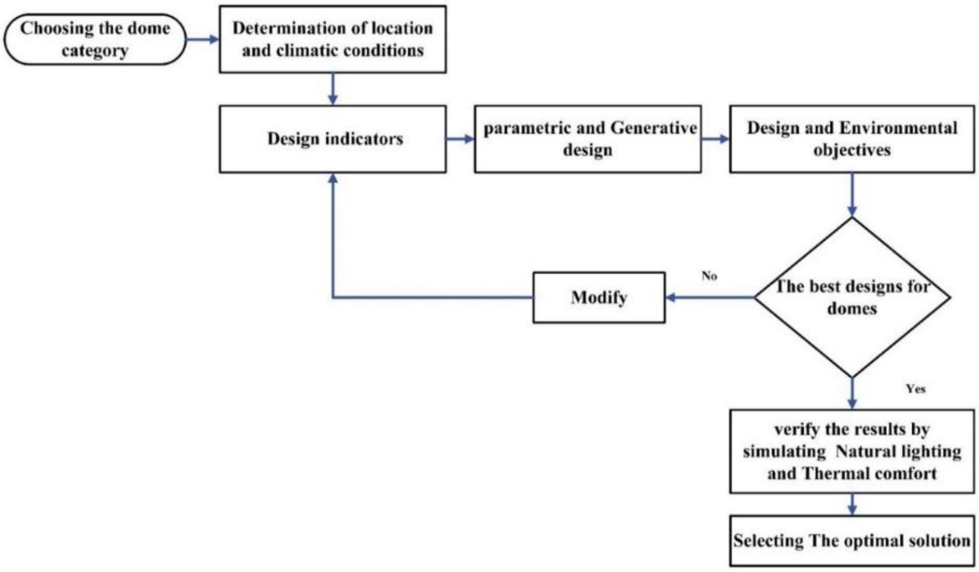


Figure 22 The methodology of the dome design

6.1 Recommendations

For the research field, The research is grounded in a set of constants, specifically the materials and construction methods. Any advancements in inputs and objectives will yield improved outcomes in terms of natural lighting and thermal comfort.

For the design process, It is essential to establish design indicators for the dome before initiating the design process. The designer must thoroughly examine the dimensions, size, and components by functional requirements and should meticulously analyze the inputs before commencing the parametric and generative design processes to ensure the attainment of optimal design solutions. It is essential to integrate parametric and generative design with techniques of improving environmental performance, which enables architects to create sustainable buildings and enhance the quality of life, without solely relying on aesthetic and functional elements.

For designers, they must study parametric design programs and programming languages, as parametric and generative design significantly enhance the designer’s creativity. They should adopt generative design as a new phase in the initial design process due to its superior capability to keep pace with technological advancements in architecture, leading to highly efficient designs from both a design and environmental perspective.

7. Conclusion

The research attempts to develop a methodology for designing contemporary domes and achieving thermal comfort and natural lighting, using parametric and generative design to obtain the best results. It also provides flexibility in designing domes through three categories according to design requirements and uses. The research also added the environmental indicators at the initial design stage by calculating thermal comfort and natural lighting to ensure that the design of domes is compatible with the environment and the surrounding climate. The research provides a straightforward methodology for architects, which gives them the freedom to form by following the same steps in the dome design process, in addition to studying the compatibility of the design with the surrounding environment and achieving thermal comfort for users.

The research used Advanced simulation programs (Multi-Objective Optimization) that depend on objectives to help reach the best results in the initial design process using design and environmental indicators and parameters and assisting in selecting the best results. Environmental simulation programs also helped verify the results extracted from the first simulation stage by conducting natural lighting and thermal comfort simulations for each solution to reach the optimal solution. Therefore, the role of simulation programs in the initial design process is essential in achieving the best results which facilitates the development of the design process.

Developing design, environmental indicators, and parameters aids in achieving superior results, particularly when utilizing modern simulation tools that allow future research to provide the best thermal comfort for users and appropriate natural lighting. Including more factors in the study, such as modifying the materials and expanding the environmental results required from the domes, could lead to additional information and raise the accuracy of the results.

Future studies should focus on developing a strategy for developing the design methodology using parametric and generative design and environmental simulation, studying the possibility of application to curved and pyramidal buildings and introducing new environmental elements such as natural ventilation, as well as studying the dynamics of openings to ensure their best environmental performance to expand the methodology to include the largest amount of buildings and various uses.

Acknowledgments

The research is part of the research plan of the Department of Architecture, Menoufia University. The paper is an excerpt from the first author's dissertation prepared under the supervision of the co-authors. The authors did not receive financial support.

شكر وتقدير

البحث هو جزء من الخطة البحثية لقسم الهندسة المعمارية، جامعة المنوفية. الورقة عبارة عن جزء من أطروحة المؤلف الأول التي تم إعدادها تحت إشراف المؤلفين المشاركين. ولم يتلقى المؤلف دعما ماديًا.

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[1] Incident solar radiation is the amount of solar radiation energy on a given surface during a given time. Values are given in units of energy per area w/m^2 and are usually the single most valuable metric for early design studies. It is sometimes called insolation and quoted in terms of energy accumulated per day or year (kwh/m2/day or kwh/m2/yr.) (Autodesk n.d.).

[2] Thermal comfort is "an impression of mind that reflects satisfaction with the thermal environment" (ASHRAE 2005).