https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: ---------

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

Domes Through Time: A Comparative Analysis of Architectural Evolution and Environmental Performance

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Abstract

The dome represents a design feature of architecture worldwide, a symbolic element in civilizations, and has an environmental role in design. The dome has been a design solution through the ages to cover buildings' roofs, especially those requiring much space without internal columns. The dome took many forms and showed the importance of its environmental design and construction roles. The research problem focuses on the environmental role of historical domes. The study depends on a significant group of domes with design, construction, and symbolic value through the ages. Then, the study will explore their environmental role, which gave the building a new factor and design value from the environmental perspective. The study depends on the case study methodology, including historical and experimental methods. The historical method analyzes the historical domes from 27 B.C. to the 19th century. The experimental method analyzes historical domes from the environmental perspective and how the domes' formation, design, and construction helped to create a distinctive internal environment. The research depends on monitoring those domes' environmental performance, analyzing some selected historical domes, exploring their internal environment using simulation programs, and measuring the environmental elements of natural lighting and thermal comfort. The research results show that developing the construction method and designing domes bodes a promising future in making buildings more efficient. In addition to having a historical aspect, the environmental roles of domes can be used recently in non-traditional buildings such as cultural and entertainment buildings, making the building environmentally efficient and providing natural lighting, ventilation, and thermal comfort.

Keywords: *The dome, Simulation, Natural lighting and ventilation, Thermal Comfort.*

1. Introduction

The dome is one of the most significant architectural symbols, and its form is recognized as an iconic symbol of many buildings. The dome is an architectural characteristic of various types of architecture worldwide and a symbolic element in civilizations with an environmental purpose.

The research problem is that most of the studies of domes focus on their structure and historical development and ignore the environmental role of these domes. This research explains the environmental aspects of historical domes and their role in achieving thermal comfort, natural lighting, and natural ventilation. The study attempts to answer the following questions: "1) What is the environmental role of the historical domes? 2) How did the historical domes help to achieve thermal comfort?"

The primary purpose is to obtain some environmental standards and improve the design of domes by analyzing historical domes, studying their environmental role, and helping to achieve thermal comfort and natural lighting. The importance of the research is studying the dome's structure evolution, analyzing these domes' environmental performance, and its role in providing thermal comfort, natural lighting, and ventilation. The research depends on the case study methodology, including historical and experimental methods. The historical method studies the history of domes and their construction stages, and the experimental method depends on analyzing the dome's form, type, dimensions, structural system, and environmental solutions.

The research examines case studies of historical domes and their development from the viewpoint of the dome structure, the construction material, and its environmental impact on natural light and ventilation. It also examines the development of domes, the construction, and environmental techniques from 27 B.C. till 1900 A.C. by choosing six domes to ensure diversity through historical significance, different shapes, and different environmental conditions to reach honest criteria about the environmental role of domes. The research discusses the world's most significant and essential domes because they better show the growth in dome construction techniques. As the Pantheon in Rome-Italy, the Hagia Sophia in Constantinople, Istanbul, Turkey; Florence Cathedral (Santa Maria del Fiore) in Florence-Italy; Saint Peter's Cathedral in Rome-Italy, Saint Paul's Cathedral in London-England, and the Capitol Dome in the United States, as shown in Figure (1).

Figure 1 Historical domes timeline Source Researchers

2. Dome definition

The dome is an architectural element like the hollow part of a sphere. It can rest directly upon a rotunda wall or a drum, or it can rest upon a system of squinches or pendentives to accommodate the transition from rectangular and square space to the polygonal or round base of the dome. The dome may be closed or opened as an Oculus with a roof lantern and cupola [1]. The dome is also "A curved structure roof that extends over an area on a circular base, generating an equal thrust in all directions. A cross-section of the dome can be semicircular, pointed, or segmented" [2]. Domes consist of two lines: 1) **A meridional line** is A curved line illustrating a vertical section slice through the axis of a rotational surface. 2) **A hoop line** is A circular line illustrating a horizontal section slice perpendicular to the axis of a rotational surface [3], as shown in Figure (2).

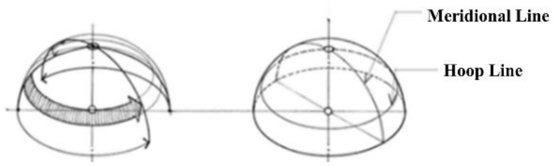

Figure 2 Meridional line and Hoop line [3]

3. Dome design and environmental impact

The dome evolved into multiple types and shapes. The idea of a dome dates back to ancient times when most people lived in circular, dome-shaped houses; many still live in such structures today [4]. The technology of construction has its impact on the dome, and it provides large volumes of clear space unobstructed by beams or columns. The larger the dome, the more efficient it becomes at enclosing space. The dome acts as a weather shield and would significantly reduce heating and insulation costs. The shape of the dome also encourages natural air circulation. The dome is the most used construction system because domes require the minimum surface area and material to complete a volume; the wind passes over the dome with less resistance; the dome design provides strength because all the structure points share the stress evenly, and the dome's shape allows environmental stress, like the movement from an earthquake, wind, or pressure from loading, to distribute throughout the structure [5] [6].

4. Methodology

The research depends on environmental simulations for the area under the domes to calculate the daylight factor and adaptive thermal comfort using modeling and environmental programs, as follows:

- Rhino and Grasshopper is a 3D computer-aided design (CAD) modeling software commonly used for parametric design.

- Ladybug is a plug-in comprising components that analyze weather data and exceptionally standard EnergyPlus weather files, and Honeybee is a plug-in composed of several elements that connect Grasshopper with EnergyPlus, Radiance, and OpenStudio for building energy, thermal, and daylight simulation.

The researchers conducted an environmental simulation for each dome based on a set of steps, as shown in Figure (3):

- The researchers modeled each dome separately according to historical studies on the shape and dimensions of the dome, the locations of the openings, the number of its layers, and the shape of the area under the dome using Rhino and Grasshopper.
- The researchers entered each dome model into the Ladybug program to convert it into a thermal model. The program could understand the parameters of the space and make sure the space was closed so that the researchers could conduct the simulation.
- Using the Honeybee program, the researchers conducted simulations for each dome to calculate the natural lighting and thermal comfort based on the weather files of the dome cities.

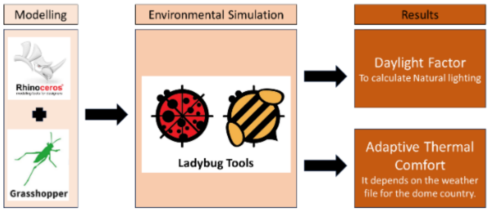

Figure 3 Environmental simulation method Source Researchers

The result from the simulation is the daylight factor, defined as the ratio of horizontal indoor to outdoor illumination by daylight under continuously overcast sky conditions, expressed as a percentage. More daylight will be available in the spaces when the daylight Factor increases. Even though spaces with an average Daylight factor of 2% or above are considered daylit, 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 [7]. Another result from the simulation is the Adaptive Thermal Comfort, which predicts the comfort conditions for naturally ventilated buildings and relates indoor design temperatures to outdoor temperatures. It depends on the understanding that occupants can adapt to, or even prefer, a wide range of conditions, expressed as a percentage. [8]

4-1 The Pantheon

The Pantheon is in Rome, Italy. Agrippa built The Pantheon around 27 B.C., and the fire destroyed it. The first Roman Emperor, Augustus, rebuilt it but was burned down again in 110 A.D. It was finished in 128 A.D. under Hadrian's reign, who became Emperor in 117 A.D. [9]. Initially, it was a temple converted to a Christian church in 609 A.D. [10]. The Pantheon is a UNESCO world heritage site as part of the "Historical Center of Rome" (no. 91) [11]. The Pantheon has a rectangular portico fronting a circular building with three rows of columns. It consists of a large hemispherical dome, 43.3m in diameter, built over a cylinder of the same diameter and height as the radius. The Oculus is 8.3m on the top of the dome [12], as shown in Figure (4).

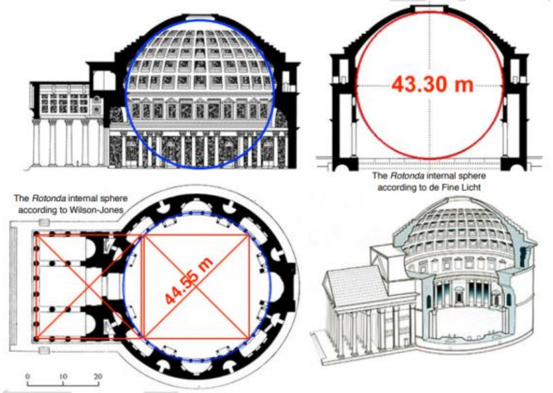

Figure 4 The dimension of The Pantheon [13]

The dome structure is a hemisphere of unique cast Roman concrete. It is a coffered dome, and the coffers have 28 vertical and five horizontal ribs. The structure of the dome and arch puts substantial weight on the lower structure and helps distribute weight evenly, reducing strain and preventing damage to the structure. The structure's wall thickness is 6.40 m. The structural thickness of the space boundary forming the dome decreases until it reaches 1.2m at the top of [14], as shown in Figure (5).

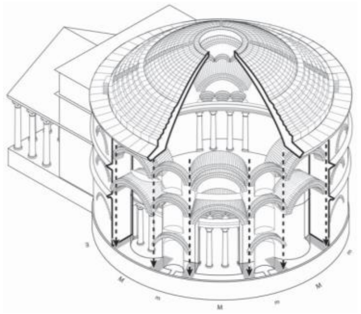

Figure 5 The structure of the Pantheon Dome [15]

The dome from an environmental perspective: In the interior part of the building, light could only pass through the Oculus and doors. The light from the Oculus moves to different spaces in the dome according to the sun's direction. From the Oculus, the sun's rays cover an area of the ground equal to 4.5% of the total area [12]. The Pantheon's passive ventilation system depends on the Oculus. Air rises by natural convection from the Oculus, and the portico entrance is the inlet for cool air at the building's base, creating an upward-moving air current. The difference in air pressure creates airflow from high to low pressure from the entrance to the Oculus [16], as shown in Figure (6). Moderate daytime illumination achieves an acceptable heat gain. The thermal massing system of The Pantheon cools the building during the hot summer months but is less effective at heating the building during the winter months because of the open Oculus [17].

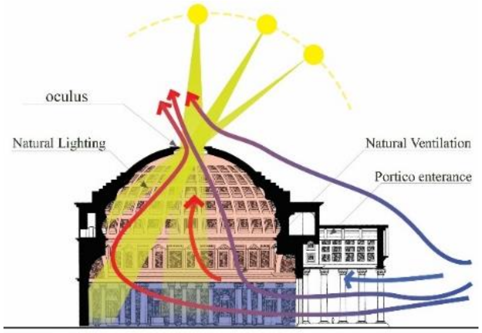

Figure 6 The natural lighting and ventilation Source Researchers

The researchers conducted an environmental simulation for the Pantheon Dome, located in Rome, Italy. The city of Rome has the highest average temperature of 21°C, the lowest average temperature of 11.5°C, and the humidity of about 71.5%. The city rises above sea level by about 52 m.

The first simulation stage is the modeling of the dome by Rhino and Grasshopper, as shown in Figure (7), and then converting it to a thermal model by Ladybug Tools and conducting the daylight factor analysis and adaptive thermal comfort to the area under the dome. The result of the daylight factor analysis is 3.37%, considered good daylight, as shown in Figure (8). The adaptive thermal comfort is 20.5% in the blue area in Figure 6, where the users and visitors can practice their activity, as shown in Figure (9).

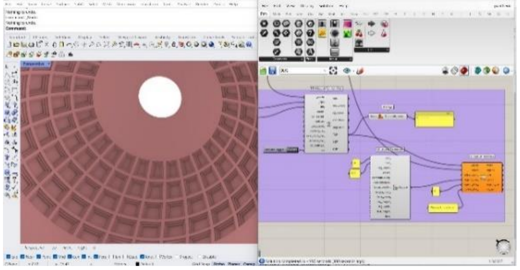

Figure 7 The Pantheon dome modeling by Rhino and Grasshopper Source Researchers dependent on Rhino and Grasshopper.

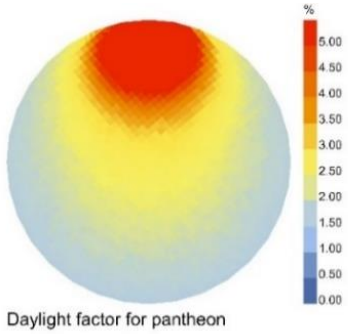

Figure 8 The Daylight Factor for the Pantheon Source Researchers dependent on Honeybee

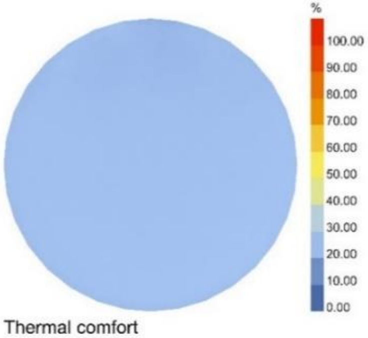

Figure 9 Adaptive Thermal Comfort for the Pantheon Source Researchers dependent on Honeybee

4-2 Hagia Sophia

Hagia Sophia is located in Istanbul, Turkey, and has been a place of worship for Christians and Muslims for 1,500 years [18]. The current Hagia Sophia was built in 537 by Byzantine Emperor Justinian I. He commissioned architects Isidore of Miletus and Anthemius of Tralles to build it. The dome collapsed because of the earthquakes, and then Young Isidoros reconstructed it, with a height exceeding the original by 6.24 m. In 1453, the Hagia Sophia was changed into an imperial mosque. Hagia Sophia was designated a UNESCO World Heritage site in 1985 [19]. The Ministry of Culture operated the Hagia Sophia Museum until 2020. In 2020, the Turkish President re-designated the Hagia Sophia as a mosque [20].

The Basilica is rectangular, and the square nave measures 31m. A central dome covered the square nave. The Basilica is 70 x 75 m in size, without including the two narthexes and the large atrium. The atrium is 48 x 32 m, while the building is 135 meters long. The Hagia Sophia dome is in the center of the building. Two half domes surround the dome, which together equals the diameters of the dome. The dome material is brick and mortar, 31.24 m in diameter and 55.6m high [21] [22], as shown in Figure (10).

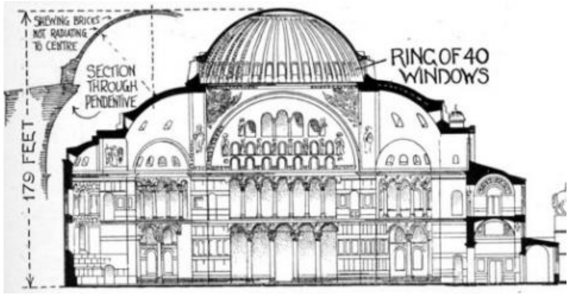

Figure 10 Section of the Hagia Sophia [22]

The dome structure: The large dome of Hagia Sophia rests upon four pendentives, forming a square and supported by four massive arches resting upon the four massive piers in the middle of the building. The two semi-domes receive the heavy thrust of the dome in the east and west [23], as shown in Figure (11). The central dome is a shell scalloped by 40 ribs, a 1.10 m width, and has 40 curved webs. "It is buttressed outside by 40 closely spaced short ribs which frame small windows." [24]

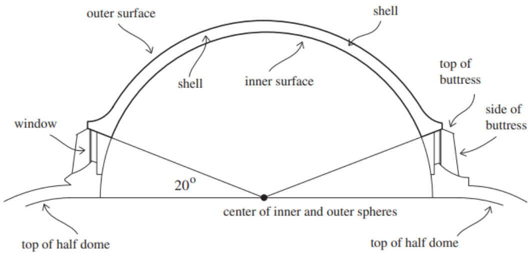

Figure 11 The structure of the dome [25]

The dome from an environmental perspective: The windows in the dome frame the sunlight when the sun's path and the window location coincide and create magnificent light beams in the interior. The contrast between the light rays and the dark surfaces creates spectacular lighting where the movement of these rays marks the passage of time in Hagia Sophia [26]. At eye level, the minor lit area is under the dome with an average daylight factor of less than 10%, as light in this area is permanently higher than eye level [27]. Natural ventilation also depends on the heated air rising towards the dome, and cold air comes from the windows at the base of the building. Solar radiation largely influences the thermal performance of the interior surface of the walls. There is no heating/cooling equipment in the building, and the energy consumption of this building is of less concern [28], as shown in Figure (12).

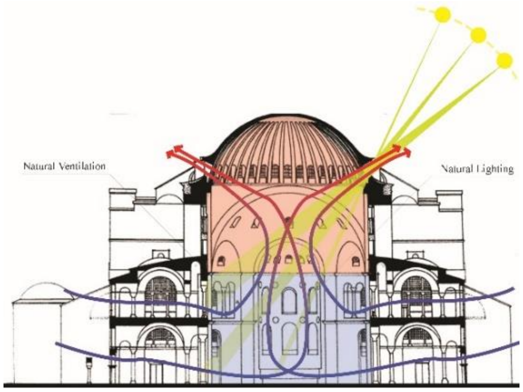

Figure 12 The ventilation and thermal performance of Hagia Sophia source: Researchers

The researchers conducted an environmental simulation for the Hagia Sophia Dome, located in Istanbul, Turkey. The city of Istanbul has the highest average temperature of 18.5°C, the lowest average temperature of 14.3°C, and the humidity of about 71%. The city rises above sea level by about 40m.

The first simulation stage is the modeling of the dome by Rhino and Grasshopper, as shown in Figure (13), and then converting it to a thermal model by Ladybug Tools and conducting the daylight factor analysis and adaptive thermal comfort to the area under the dome. The result of the daylight factor analysis is 2.54%, considered daylit, but electric lighting may still be required, as shown in Figure (14). The adaptive thermal comfort is 22.9% in the blue area in Figure 12, where the users and visitors can practice their activity, as shown in Figure (15).

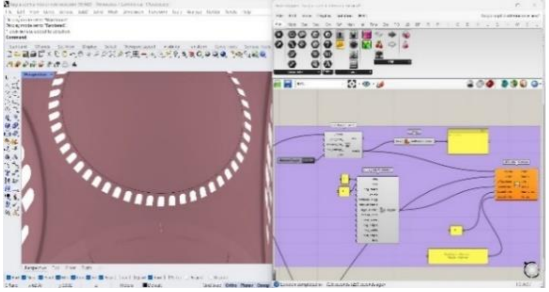

Figure 13 The Hagia Sophia dome modeling by Rhino and Grasshopper Source Researchers dependent on Rhino and Grasshopper.

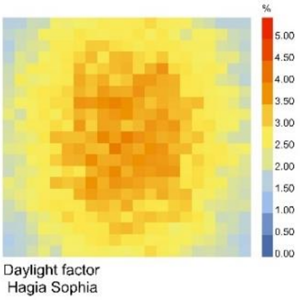

Figure 14 The Daylight Factor for the Hagia Sophia Source Researchers dependent on Honeybee

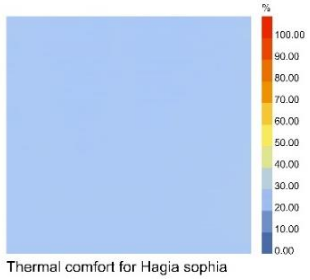

Figure 15 Adaptive Thermal Comfort for the Hagia Sophia Source Researchers dependent on Honeybee

4-3 Florence Cathedral Dome

Florence Cathedral (Santa Maria del Fiore) is in Florence, Italy. It is the result of years of work that covered over six centuries of history. In 1296, the famous Arnolfo di Cambio started the cathedral's construction. After Di Cambio's death, from 1334 to 1337, The Giotto di Bondone was nominated to oversee the construction works. He designed and built the Bell Tower next to the cathedral. From 1420 to 1436, Brunelleschi started the construction of the dome. From 1436 to 1471, a large Lantern with a copper ball was made on top of the dome. From 1864 to 1887, Emilio de Fabris and Luigi del Moro finished the construction of the facade [29], as shown in Figure (16). Florence Cathedral is a UNESCO World Heritage site, part of the "Historical Center of Florence, 1982", No.174 [31].

Figure 16 The Florence Cathedral today [30]

The cathedral is 153 m long, 38 m wide across the nave and aisles, and 90 m across the transepts. The plan is a modified Latin cross, with a nave of only four huge square bays, relatively narrow aisles (each half the width of the nave), and an octagonal crossing. The Florence Cathedral dome is the largest masonry dome in the world [32], as shown in Figure (17).

Figure 17 The Florence Cathedral Section [22]

The dome structure: The dome is 45.52 meters in diameter and 90 meters in height. It was a challenge to build a dome without centering. Brunelleschi decided to make the dome as light as possible (double shell structure, a pointed dome). He placed eight primary ribs at the points of the octagon and 16 minor ribs (two in the space between every two primary ribs), all tied together by lateral bands [23]. Brunelleschi used bricks for the dome. Herringbone masonry was the revolutionary method by which bricks were sloping inward. The dome had an opening in the center for lighting (Oculus). Over the Oculus, there is a Lantern that is 16 meters high and weighs approximately 10% of the total dome, and the total height of the dome and Lantern is 114.5m [33], as shown in Figure (18).

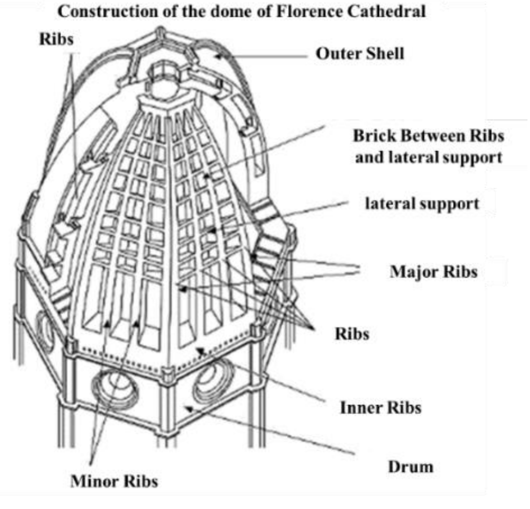

Figure 18 The construction component of the dome [30]

The dome from an environmental perspective: The Lantern is vital to the architectural ensemble. The marble lantern serves the function of covering the Oculus while still allowing light to enter the cathedral. The Lantern is a rooftop structure with openings for lighting and ventilation [34], as shown in Figure (19). Solar radiation does not influence the thermal performance of the interior surface of the walls because of the double shell. A remarkable environmental event occurs in Florence's Cathedral on the day of the summer solstice yearly when a single sun ray passes through the bronze disk's hole at the dome's top. The spectacle lasts a few minutes and then vanishes, marking the year's longest day [35].

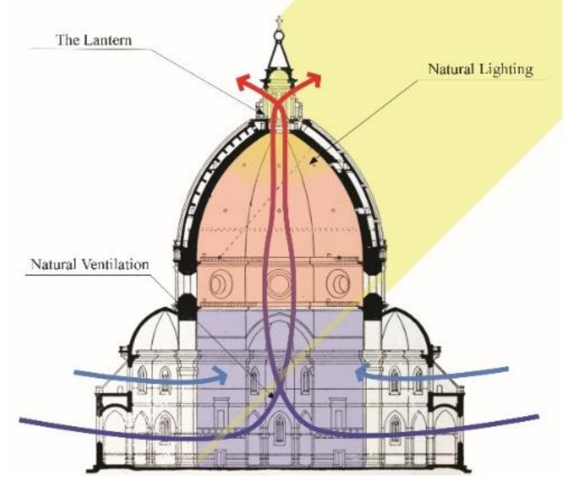

Figure 19 The Lantern above the Oculus is the source of lighting and ventilation source: Researchers.

The researchers conducted an environmental simulation for The Florence Cathedral dome, located in Florance, Italy. The city of Florence has the highest average temperature of 19.4°C, the lowest average temperature of 6.9°C, and the humidity of about 75.7%. The city rises above sea level by about 51m.

The first simulation stage is the modeling of the dome by Rhino and Grasshopper, as shown in Figure (20), and then converting it to a thermal model by Ladybug Tools and conducting the daylight factor analysis and adaptive thermal comfort to the area under the dome. The result of the daylight factor analysis is 0.905%, considered daylit, but electric lighting is required for the lighting, as shown in Figure (21). The adaptive thermal comfort is 18.64% in the blue area in Figure 19, where the visitors can practice their activities, as shown in Figure (22).

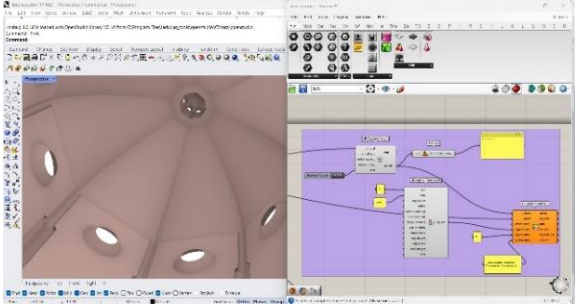

Figure 20 The Florence Cathedral dome modeling by Rhino and Grasshopper Source Researchers dependent on Rhino and Grasshopper.

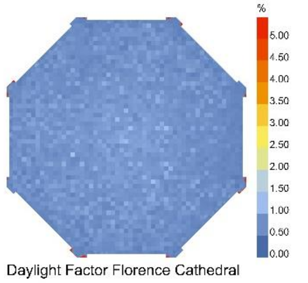

Figure 21 The Daylight Factor for The Florence Cathedral Dome Source Researchers dependent on Honeybee

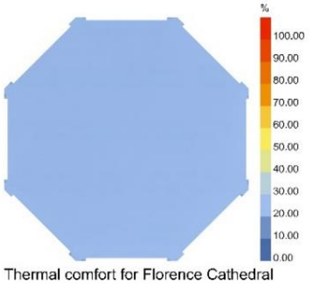

Figure 22 Adaptive Thermal Comfort for The Florence Cathedral Dome Source Researchers dependent on Honeybee

4-4 Saint Peter's Basilica

Saint Peter's Basilica is in Rome, Italy. Emperor Constantine commissioned the building of Old St. Peter's Basilica between 326 and 333 [36]. The construction took roughly 40 years to complete and finished in 360. Between 1503 and 1513, Pope Julius II decided to demolish the old Basilica and rebuild a new Basilica, and Donato Bramante prepared the original plan inspired by The Roman Pantheon. The project stopped in 1514, and Many architects developed the plan for the Basilica until Michelangelo returned to Bramante's plan but simplified it. Michelangelo died in 1564, and finishing the dome went to Porta. The work stopped repeatedly but continued in 1607, and the Basilica appeared in its new image in 1615 [37], as shown in Figure (23). St. Peter's Basilica was a UNESCO World Heritage site in 1980 [38].

Figure 23 The new St. Peter Basilica [37]

St. Peter's Basilica is the most massive church in the world, spanning over 23,000m^2 [36]. The Basilica has a length of 218 m and a height of 136 m, including the dome. Like most basilicas, this one also consists of traditional naves, aisles, and altars [39].

The dome structure is supported on the drum with pendentives and further down by four massive arches between pentagonal piers, as shown in Figure (24). The inner diameter of the dome measures 41.7 m, and the external diameter is 58.90 m. The total height of the dome from the road to the top of the cross is 133 m. The dome consists of two masonry shells interconnected by 16 ribs, and the two shells merge into one, 10 m above the dome's springing. The inner dome thickness is 1.4 m, and the outer dome is 0.7 m. The thickness is 3 m at the dome's base, which connects with the drum, and the overall thickness is 5 m at the top, as shown in Figure (25). The Lantern is at the top of the dome, and Its inner diameter is 7 m. The buttresses consist of stone columns connected to the drum. Window openings measure 2.5 x 5 m between the buttresses, starting 3 m above the base of the drum [40].

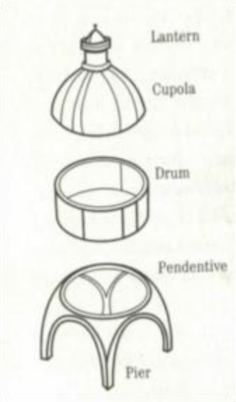

Figure 24 The component of the dome [41]

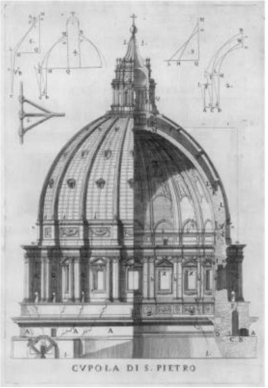

Figure 25 Geometrical and structural details of the dome [42]

The dome from an environmental perspective: Natural light streams through a set of windows in the drum of the dome and the Oculus into the cathedral and illuminates the interior of St. Peter's, making the dome float above a circle of light. The lanterns became an iconic feature as a practical method for providing enough weather protection while enabling gasses to leave and fresh air to enter a building. The Lantern is still a valuable tool for ventilation and letting in extra sunlight [43] [27], as shown in Figure (26).

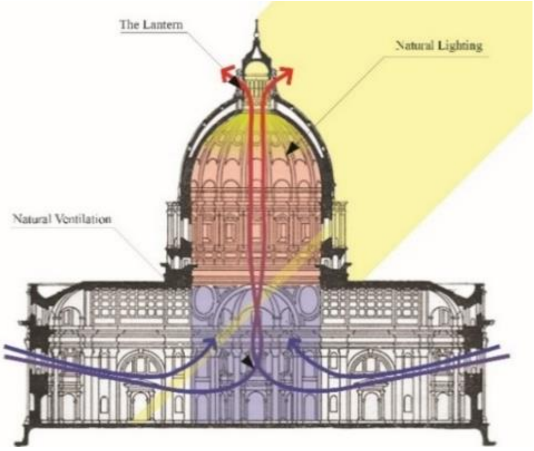

Figure 26 The thermal performance of St. Peter source: Researchers

The researchers conducted an environmental simulation for Saint Peter's Dome, located in Rome, Italy. The city of Rome has the highest average temperature of 21°C, the lowest average temperature of 11.5°C, and a humidity of about 71.5%. The city rises above sea level by about 52m. The first simulation stage is the dome modeling by Rhino and Grasshopper, as shown in Figure (27), and then converting it to a thermal model by Ladybug Tools and conducting the daylight factor analysis and adaptive thermal comfort to the area under the dome. The result of the daylight factor analysis is 1.46%, considered daylit, but electric lighting is required for the lighting, as shown in Figure (28). Moreover, the adaptive thermal comfort is 20.63% in the blue area in Figure (26), where the visitors can practice their activities, as shown in Figure (29).

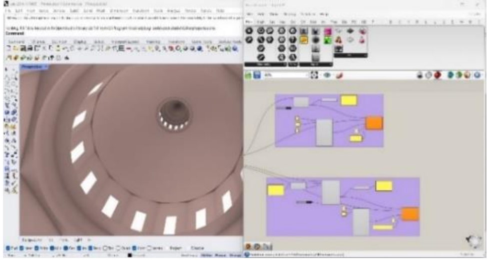

Figure 27 The St. Peter Cathedral dome modeling by Rhino and Grasshopper Source Researchers dependent on Rhino and Grasshopper.

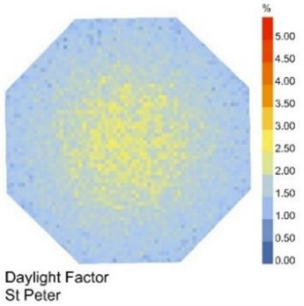

Figure 28 The Daylight Factor for St. Peter Cathedral Dome Source Researchers dependent on Honeybee

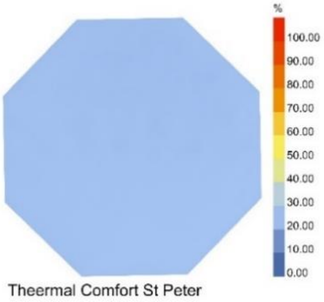

Figure 29 Adaptive Thermal Comfort for St. Peter Cathedral Dome Source Researchers dependent on Honeybee

4-5 Saint Paul's Cathedral

Saint Paul's Cathedral is the most recognizable monument in London, England. In 1669, Sir Christopher Wren took on the task of St. Paul after the Great Fire of London. He took his inspiration from St Peter's Basilica. It is the second largest in Britain and the most delicate dome in the world. The cathedral was officially completed in 1711, and construction continued for 36 years [44]. The cathedral is a Latin cross plan with a nave, transept, and twin bell towers on either side of the central entrance. The dimensions of the nave are 158 x 37m, and the dome height is 85m [44], as shown in Figure (30).

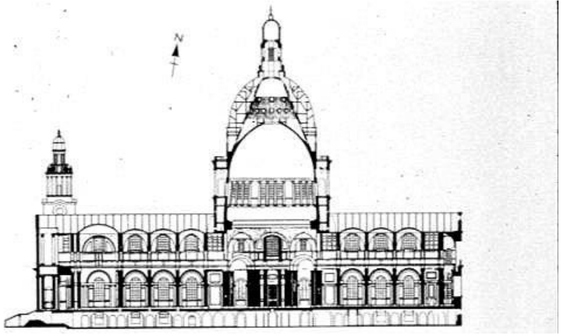

Figure 30 St. Paul's Cathedral Section [22]

The dome structure: The dome of St. Paul is the second largest cathedral dome in the world, with a diameter of 30.7m. St. Paul's Cathedral has an innovative triple dome design. The inner dome rises on the circular drum and is noticeable inside the cathedral, and A brick cone rises above this inner dome to support the 850-ton Lantern. This brick cone also supports the wooden rafters and structure of the outer dome, as shown in Figure (31). The brick cone is the weight-bearing structure, whereas the inner and outer domes are only ornamental. The dome is on the pendentive and rests on eight arches. Thirty-two radiating buttresses extend from the drum, each ending with three-quarter columns, creating a peristyle. [23] [45].

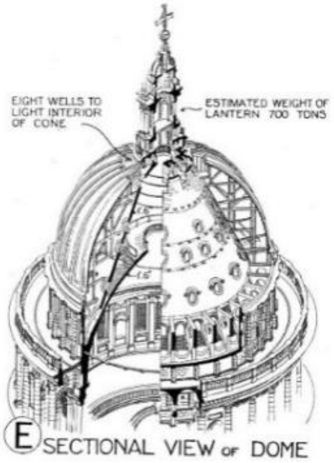

Figure 31 The dome of St. Paul's Cathedral [22]

The dome from an environmental perspective: The Lantern softly lit the dome, and it is a bright Oculus. The interior receives ample natural light from 24 large windows in the dome. Also, the Lantern provides a functional solution for allowing ventilation to a building [46] [47], as shown in Figure (32).

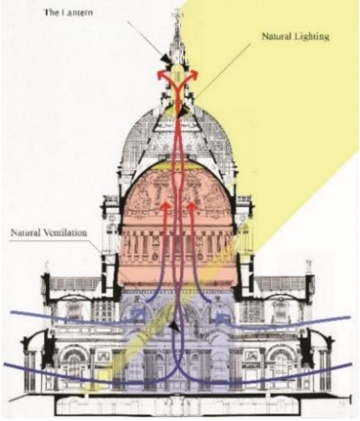

Figure 32 The natural light and ventilation source: Researchers

The researchers conducted an environmental simulation for Saint Paul's Dome, located in London, England. The city of London has the highest average temperature of 14.58°C, the lowest average temperature of 7.85°C, and a humidity of about 78.8%. The city rises above sea level by about 21m.

The first simulation stage is the modeling of the dome by Rhino and Grasshopper, as shown in Figure (33), and then converting it to a thermal model by Ladybug Tools and conducting the daylight factor analysis and adaptive thermal comfort to the area under the dome. The result of the daylight factor analysis is 1.54%, considered daylit, but electric lighting is required for the lighting, as shown in Figure (34). Moreover, the adaptive thermal comfort is 8.87% in the blue area in Figure 32, where the visitors can practice their activities, as shown in Figure (35).

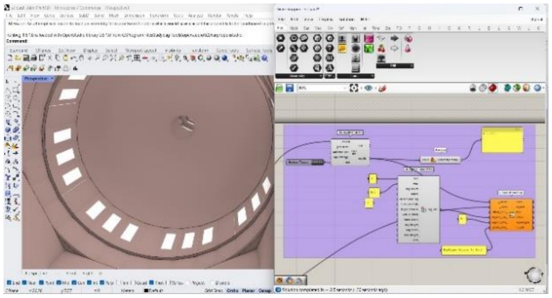

Figure 33 The St. Paul Cathedral dome modeling by Rhino and Grasshopper Source Researchers dependent on Rhino and Grasshopper.

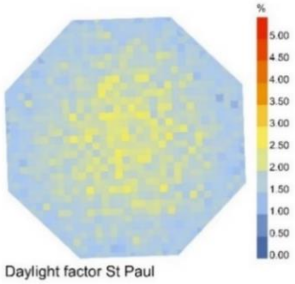

Figure 34 The Daylight Factor for St. Paul Cathedral Dome Source Researchers dependent on Honeybee

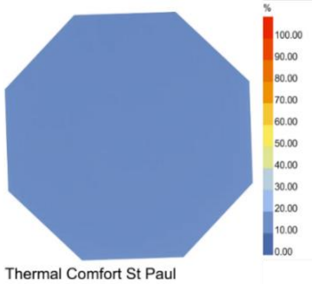

Figure 35 Adaptive Thermal Comfort for St. Paul Cathedral Dome Source Researchers dependent on Honeybee

4-6 The Capitol Building

The Capitol building is in Washington, D.C., United States. The Capitol is the building of Representatives and other critical political committees. The United States has developed and rebuilt the capitol building several times [48] [49]. On 5 Apr. 1793, President Washington approved the initial version of The Capitol building planned by Dr. William Thornton. In 1800, The building started with the right-wing and temporary conference room. Then, the south wing was built over the temporary building. On 24 Aug. 1814, the British military set fire. In 1826, the entire Capitol Building was restored, including a copper-covered wooden dome atop the center section. In 1851, The Capitol extension project started and added new wings that fit the existing architectural style. In 1855, Thomas Walter designed a new dome for the Capitol. The new dome was supposed to be cast iron, with the Statue of Liberty above. American artist Thomas Crawford completed the new dome and progressive Statue raising in 1863 [49], as shown in Figure (36).

Figure 36 The Capitol building source: https://globalparliamentofmayors.org/

The U.S. Capitol Building was a landmark of 19th-century neoclassical architecture. The Capitol covers an area of 16187.4 m^2, has a floor area of approximately 651543.9 m^2, and has five levels. The length from north to south is 229 m, and the greatest width is 106.7m. Its height above the baseline to the top of the Statue is 88m [49]. The Rotunda is a circular ceremonial space under the dome on the second floor. The dome is 29m in diameter and rises 55m from the second floor [50], as shown in Figure (37).

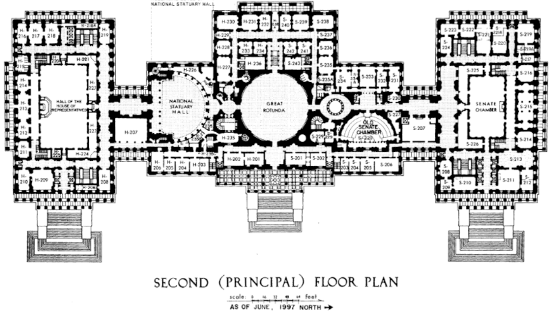

Figure 37 The Capitol building's second-floor plan [51]

<u>**The dome structure**</u> is currently the world's largest cast iron dome. The dome structure comprises three distinct components [52]. The outer dome is marble with hollow brick backup and embedded steel tension bands. The middle dome is a conical steel structure supporting the dome's steel-framed Lantern, which consists of steel column ribs connected to the tension ring at the base of the outer dome. The inner dome forms the rotunda ceiling, as shown in Figure (38). The dome is raised on a high drum in two parts: a lower portion encircled by a colonnade on the outside, an interior surface pierced by windows, and an upper part. A Lantern crowned with decorative statuary

completes the ribbed dome on top. The dome has 36 arched ribs bearing 36 paired pillars and sets on 36 pairs of cast iron brackets included in the masonry walls [53]. The dome was cast iron and lifted into place by steam-powered machines called derricks. [49]

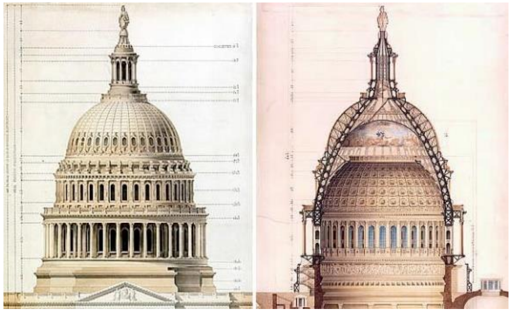

Figure 38 The Capitol dome section and elevation [54]

The dome from an environmental perspective: The natural light comes from drum windows, the windows on the upper part of the Rotunda, above the third-floor roof, but below the inner dome, as shown in Figure (39). The natural ventilation in the dome depends on four round copper relief vents on the roof, located at four corners, allowing hot air to escape [55] [52].

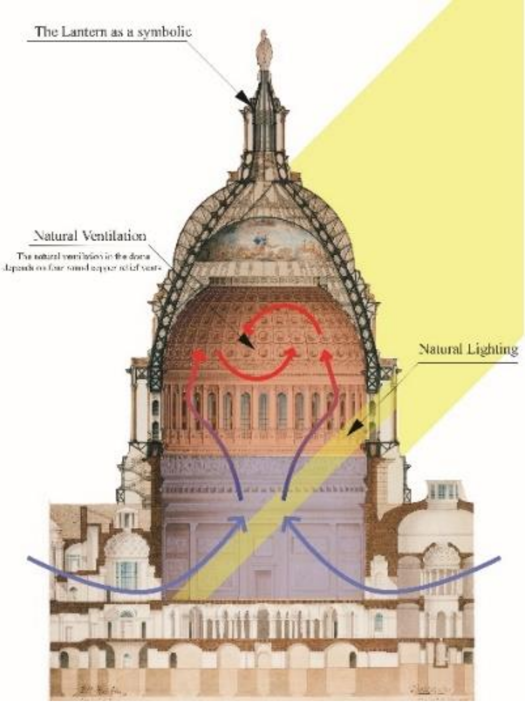

Figure 39 The natural lighting and ventilation of the Capitol Dome source: Researchers

The researchers conducted an environmental simulation of The Capitol Dome, located in Washington, D.C., the United States. The state of Washington, D.C. has the highest average temperature of 11°C, the lowest average temperature of 0.5°C, and a humidity of about 75.5%. The city rises above sea level by about 125m.

The first simulation stage is the modeling of the dome by Rhino and Grasshopper, as shown in Figure (40), and then converting it to a thermal model by Ladybug Tools and conducting the daylight factor analysis and adaptive thermal comfort to the area under the dome. The result of the daylight factor analysis is 20.1%, which may appear significantly daylit; however, visual and thermal conditions may be unsuitable, as shown in Figure (41). The adaptive thermal comfort is 19.92%, in the blue area in Figure 39, where the visitors can practice their activities, as shown in Figure (42).

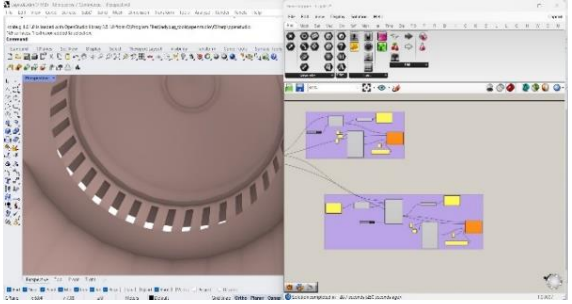

Figure 40 The Capitol Dome modeling by Rhino and Grasshopper Source Researchers dependent on Rhino and Grasshopper.

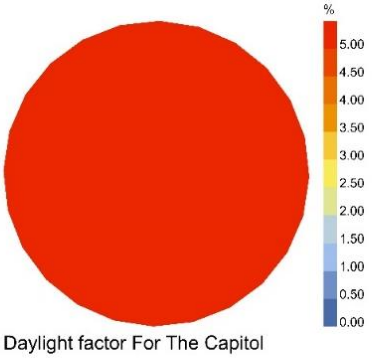

Figure 41 The Daylight Factor for The Capitol Dome Source Researchers dependent on Honeybee

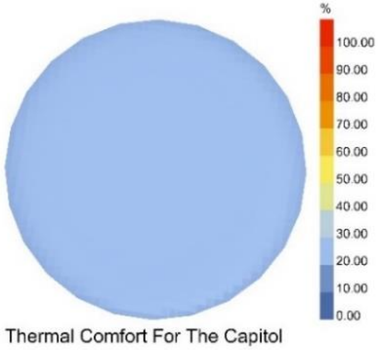

Figure 42 Adaptive Thermal Comfort for The Capitol Dome Source Researchers dependent on Honeybee

5. Results

Example	**The Pantheon**	**Hagia Sophia**	**Florence Cathedral**	**Saint Peter's Cathedral**	**Saint Paul's Cathedral**	**The U.S. Capitol Building**
Location	Rome, Italy	Istanbul, Turkey	Florence, Italy	Rome, Italy	London, England	Washington, D.C., USA
Coordinates	41.9028° N, 12.4964° E	41.0082° N, 28.9784° E	43.7696° N, 11.2558° E	41.9028° N, 12.4964° E	51.5072° N, 0.1276° W	38.9072° N, 77.0369° W
Architect	Agrippa and Emperor Hadrian	Isidore and Anthemius	Filippo Brunelleschi (the dome)	Michelangelo Buonarroti	Christopher Wren	Thomas Walter
Construction Date	27 B.C. to 128 A.C.	537 A.C.	1420 to 1436	1564 to 1615	1675 to 1711	1857 to1863
The dome Dimensions	The dome is 43.3m in diameter and height.	The dome diameter is 31.24m and 55.6m in height.	The dome diameter is 45.52m and 114.5m in total height.	The dome diameter is 41.7m and 133m in total height.	The dome diameter is 30.7m and 111m in total height.	The dome diameter is 29m, and the height is 55m.
Dome Type	Hemispherical dome.	The dome on four pendentives.	The double-shell dome	The double shell dome is on the drum with pendentives.	The triple shell dome is on the drum with pendentives.	A paraboloid dome consists of triple shells.
The Dome Structure	It is a coffered dome, and the coffers have 28 vertical and five horizontal ribs. It puts substantial weight on the lower structure and helps distribute weight.	The dome rests upon four pendentives, forming a square, and four massive arches rest upon the four massive piers in the middle of the building.	The double shell structure is an inner heavier and lighter outer. It consists of eight primary ribs at the points of the octagon and 16 minor ribs.	The dome consists of two shells and 16 ribs interconnect the two shells. The dome is supported on the drum with pendentives and further down by four massive arches between piers.	The dome consists of three layers. The inner dome rested on the circular drum, and pendentives were on eight piers and arches. A brick cone rose above this inner dome to support the Lantern. This brick cone also supports the wooden structure of the outer dome.	The outer dome is marble with hollow brick backup and embedded steel tension bands. The middle dome is a conical steel structure supporting the dome's steel-framed Lantern. The inner dome forms the rotunda ceiling.
Structure Material	Roman Concrete	Light brick	Bricks in a herringbone pattern	the dome consists of an inner and outer masonry shell	Bricks in the inner layer and the cone, and Wood in the outer layer	Marble and bricks in the outer layer. Casted iron in the middle and inner layers
Natural Light	Direct lighting from the Oculus.	Indirect lighting comes from the Lantern covering the Oculus and 40 windows in the dome.	Indirect lighting comes from the Lantern.	Indirect lighting comes from 16 windows in the drum and the Lantern.	Indirect lighting comes from the Lantern and 24 windows in the dome.	Indirect lighting comes from 36 drum windows.
Natural Ventilation	The Oculus creates airflow into the portico entrance and out of the Oculus	The heated air rises towards the dome, and cold air comes from the windows at the base, creating airflow in the building	The Lantern is a rooftop structure with openings for ventilation	The Lantern provides building ventilation	The Lantern allows hot air to escape from the building	There are four round copper relief vents in the dome to relieve the dome area

Simulations Results

Example	**The Pantheon**	**Hagia Sophia**	**Florence Cathedral**	**Saint Peter's Cathedral**	**Saint Paul's Cathedral**	**The U.S. Capitol Building**
Daylight Factor	3.37%	2.54%	0.905%	1.46%	1.54%	20.1%
Thermal comfort	20.5%	22.9%	18.64%	20.63%	8.87%	19.92%

6. Discussion and implications

6-1 Discussion

The dome developed throughout history from 27 B.C. to the 19th century, and The Pantheon dome influenced the following domes, and every civilization sought to increase the dimension of the dome. The Florence dome had a larger diameter of 45.52m, and the St. Peter dome had the highest height, 133m, through this period. The dome's shape progressed from the hemispherical dome to the dome on pendentives to the double and triple shell dome.

These examples of domes played a primary role in providing direct and indirect lighting. The Pantheon depended on the Oculus for direct natural lighting; the rest of the domes depended on the Lantern, covering the Oculus, and the windows in the drum for indirect natural lighting. However, the Capitol dome depended only on the windows in the drum. These historical domes provided natural ventilation by creating airflow in the building when the heated air rose towards the dome's top and escaped from the Oculus and the Lantern. The Oculus and the Lantern were responsible for the natural ventilation, but the Capitol dome depended on four round copper relief vents.

The simulation results showed that all the historical domes are responsible for the natural daylight in the historical building. The Pantheon has significant natural daylight, with a daylight factor of 3.37%. The Florence Cathedral has a minimum daylight factor of 0.905%, which still needs electrical lighting, and the Capitol has a maximum daylight factor of 20.1%, which causes unsuitable visual and thermal conditions. According to the simulation results, all the historical domes achieve adaptive thermal comfort within a range of 20%, which explains the dome's importance in achieving thermal comfort through natural ventilation and natural conditions. The Hagia Sophia Dome has the highest thermal comfort of 22.9%, and the St. Paul Cathedral Dome has the lowest thermal comfort of 8.87%.

Through the results of the simulation, A Spearman correlation was performed using the SPSS software to calculate the relation between the daylight factor, Adaptive Thermal comfort, diameter, height, and number of layers for each dome, as shown in Figure (42) and the results from the analysis are that:

- There is a significant inverse correlation between the daylight factor and the diameter and height of each dome, which are -0.60 and -0.886, respectively.
- There is a significant inverse correlation between the adaptive thermal comfort and the number of layers, which is -0.717.

The analysis explained that the lower the diameter and height of the dome, the greater the daylight factor, moreover the fewer layers in the dome, the better the adaptive thermal comfort, and vice versa.

The statistical analysis interpreted the high value of the daylight factor in the Capitol Dome because it has the lowest diameter and height among these historical domes, and it also interpreted the high value of thermal comfort in St. Paul's Dome because the number of its layers reached three layers.

The results of the statistical analysis show a correlation between natural lighting, thermal comfort, and the diameter, height, and number of layers of the dome. However, some variables may affect the results, such as the climate conditions surrounding each dome, temperature, and humidity, as well as geographical conditions and height above sea level, which affect wind speed and natural ventilation.

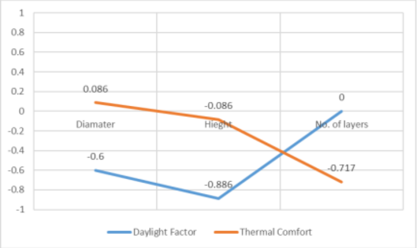

Figure 43 Spearman Correlation Results Source Researchers

6-2 Implications

The study dealt with six important historical domes, as these domes are in different places around the world with different climatic conditions and geographical factors. However, they achieved good rates of thermal comfort and natural lighting, which indicates that the form and proportions of the dome, as well as the number of layers, have an essential role in generating an appropriate internal environment.

7. Limitations

The study revealed the difficulty of taking real measurements for the six domes, and therefore environmental simulations were used to calculate natural lighting and thermal comfort.

The climate and geographical conditions surrounding each dome, including the outer perimeter, and the characterization of building materials in the simulation process will increase the accuracy of the results.

Simulation analysis has limitations, such as the use of weather files for each city, and these files may need to be constantly updated to ensure the accuracy of the results. Another limitation is the need to model the dome in a simplified way to make a thermal model, which raises doubts about the accuracy and efficiency.

8. Conclusion

The dome is the most effective form in history. The domes initially appeared in religious buildings, and because they have symbolic, environmental, and structural value, they began to appear in non-traditional buildings such as political, cultural, and entertainment buildings.

The development of construction methods and materials for the dome will improve the dome's form and increase its dimensions because the dome has a significant structure and provides a large area with no columns or interruptions. Moreover, the dome form has not become the form of a specific historical period because it is flexible, suitable for development, and the most appropriate form of all civilizations.

The historical domes improved the indoor environment by providing natural lighting and ventilation to achieve thermal comfort. The natural lighting came from the drum's windows, Lantern, and Oculus. They also created airflow when the heated air raised to the top of the dome and then escaped through the Oculus or the Lantern, providing a natural ventilation system.

Developing the dome's form and dimensions will improve the natural lighting. Also, the double and triple shells helped provide thermal insulation and protect the indoor environment from solar radiation, but it affects the thermal comfort percentage.

A set of criteria can be extracted that help develop the environmental performance of domes, which increases thermal comfort and natural lighting by paying attention to the domes' dimensions, the openings' distribution, the number of layers, and the materials.

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