Improving Daylighting and thermal performance in SPORTS HALL buildings with phase change materials (PCM) to reduce energy consumption

Dr. Marwa Mohamed. Abbas
1, 2 Lecturer of Architecture Engineering, Modern Academy for Engineering & Technology, Cairo, Egypt, miroda2020@gmail.com
Dr. Ahmed Nour El-Din
Lecturer of Architecture Engineering, Modern Academy for Engineering & Technology, Cairo, Egypt, dr.ahmed.nour020@gmail.com

Abstract:
The research paper proposes a model for using phase change materials to improve the visual and thermal performance of indoor sports halls, with the goal of achieving maximum natural lighting during the day and improving thermal performance, thus optimizing energy consumption. This is accomplished by employing (PCM Translucent) for window openings and PCM paraffin for wall thermal insulation.
To achieve the research's goal, a sports building in Cairo with an area of 4028 m2 with gymnastics and basketball halls was chosen, The value of daylight, thermal performance, and rate of energy consumption of the case study were all measured using simulation programs. The findings revealed that the internal spaces do not fulfill measuring norms. LEED, whether in terms of daylight quality or thermal performance, and the analysis showed that the northern façade of the building obtains the greatest quantity of sunlight, while the southern façade is the most exposed to the sun's harmful rays.
Experiments were conducted to determine the best ratio of (WWR%) openings that could be utilized in the northern façade and ceilings to achieve maximum natural lighting during the day using the transparent PCM material and the simulation program to the different widow wall ratios (25, 35, and 45%). The results showed that as the percentages of openings in the wall and ceiling increased, but when they increased 45% of the side effect "light scattering" began to appear, the results showed improved thermal performance by using (PCM paraffin) as a thermal insulator to insulate the southern façade.
Comparing the simulation results of the gymnasium spaces before and after development revealed a clear improvement, with the value of daylight improved by 163%, the temperature improved by 27%, the humidity improved by 27%, and solar radiation improved by 70%, energy consumption was reduced by 67% As a result.

Keywords:
Sports Hall, Daylighting, window wall Ratio (WWR%), phase change materials (PCM), energy consumption

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1. Introduction:
Energy efficiency and comfort in daylight are among the most important aspects of sustainable building design, and public health for humans is the primary focus of research [1]. Practicing sports activities is considered one of the most important key factors for maintaining human health, and physical and mental fitness. Therefore, gymnasiums for sports activities must be characterized by sustainability and provide a healthy climate for users. This is done by creating the internal conditions of these halls to be suitable for the comfort of the human body, especially the visual senses and thermal properties (lighting efficiency - temperature - humidity degree), the users feeling of visual comfort necessary for good vision, as well as thermal comfort, which enhances the physical and muscular activity of players. In order to achieve these goals, we must take into account one of the goals of sustainability, which is reducing energy consumption and working to rationalize consumption, and this is what the presented research paper addressed. This is done by choosing a sports building in one of the Egyptian clubs in Cairo. This building consists of two halls bordered by a basketball court and the second is a gymnastics hall.
The means of lighting the building are fluorescent lamps. As for the means of improving the temperature of the space, it is the adaptations. There is a feeling of dissatisfaction for the majority of the users of the halls of the building and their lack of feeling of pleasure during training and matches. The quality of the lighting of closed stadiums is an essential factor in the comfort of the eyes, and achieving the quality of lighting and reflective surfaces, with the need to consider the equal intensity of lighting. All over the sports halls [2].
The research paper dealt with the study of the building and the thermal characteristics (temperature, humidity, and solar radiation) inside the gyms, as well as the rate of energy consumption throughout the months of the year, taking into account the months with the most energy consumption (March and August).

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The research dealt with treatment through several axes, the first (WWR%) of which is increasing the proportions of openings in Walls to double the natural lighting during the day by making optimal use of direct sunlight and its penetration into the interior space during the day. Secondly, a window is opened in the ceiling of the halls to allow direct sunlight to penetrate into the interior of the halls, Thirdly, use PCM TRANSLUCENT as a transparent material for windows [3]. It is a material that allows light to pass through, stores heat does not allow it to pass through, and uses PCM paraffin to insulate the walls.

The results of the study showed that the northern facade is the best for making modifications and increasing the proportion of window openings while avoiding making openings in the southern facade, as it is the facade most exposed to solar radiation, which causes light scattering, glare, and reflection problems, which affects vision [4].

Using the simulation program, the researcher was able to conduct experiments to choose the best ratio of wall and ceiling voids that could achieve the maximum improvement of the visual and thermal properties within the building's hall space when using the appropriate PCM material. The ratio of 45% for wall and ceiling openings was the best, and the results were recorded after the modifications and a complete comparison of the properties was made. Optical and thermal before and after the modification, and came up with the percentages of improvement achieved as a result of the modifications. The value of energy consumption before and after the modification was also compared, and the percentage of savings in energy consumption was evaluated.

2. Literature Review:

In one of the researchers conducted by Kisilewicz (2015) on a gym [5]. he noticed a sharp rise in the temperature of the hall in the summer, which reduced (90% in cases of extreme heat) of the hall's visitors. The research reached results that indicate the possibility of improving the temperature of the hall's vacuum through several procedures. Including installing solar curtains, and discharging the heat in the hall's emptiness at night by using air extractors to pull hot air out of the building, in addition to using mechanical ventilation.

The researchers Rajagopalan and Luther [6], also reached results with a study on phase change matter (PCM), which are several types that change their state from solid to liquid due to an increase in temperature and then return to their solid state when the temperature decreases. These materials store energy during their melting and recover it during their freezing, and this process is known as the name of latent thermal energy, The phase material is characterized by its ability to store thermal energy more than 14 times per unit volume of traditional materials.

The researcher Jun Hung Li [7], reached important results after studying many phase change materials and subjecting them to examination. Paraffins were among the most prominent of these types as a thermally insulating material and it has significant heat storage properties due to their wide use for LH TES applications because of their good thermal properties.

3. Theoretical Part:

3.1 PCM as Innovative Building Materials

- The PCM material was chosen as a building material in the research with the goal of improving daylight and thermal performance inside sports halls because it suits the climatic conditions of Cairo, where the temperatures of the spaces allow the material to melt in the event of a high temperature of the space and its recovery when the temperature drops at night [8].
- PCM paraffin RT28HC, which is part of the organic PCMs, is used as an insulating material for walls and ceilings, as it is compatible with building materials, non-corrosive, and has a high heat storage capacity.
- PCM TRANSLUCENT was chosen as a transparent material for treating windows, as it allows daylight to pass through while achieving good thermal insulation, thus improving the internal thermal properties of sports halls [9].

Table 1: Physical and thermal properties of PCM RT28HC.

Property	Value
Area of melting/congealing	27–29 C
heat capacity specific	2 kJ kg1 K1
7.5% latent heat capacity	250 kJ kg
Temperature conductivity	0.2 W m1 K1
% Volume growth	12.5
The PCM flashpoint	

3.2 LEED standards version 4 Daylight Metrics [10]

The Lighting Engineering Society (LES) issued the code "3128- LM 2012" as appropriate requirements for daylight performance, which was adopted and implemented as a standard in 2014v4 LEED. The LEED system provides three ways for measuring daylight performance, all of which use simulation. There is also a DF system, which is a unit of measurement that displays "the ratio of the level of internal lighting of buildings to the level of natural lighting outside buildings in accordance with LEED standards, [11,12,13]. "According to LEED, there are three ways to measure daylight performance according to LEED:

- **Simulation Option 1:** SDA (300 lux, 50 hours) and ASE (1000 lux, 250 hours).
- **Simulation Option 2:** Simulation: Illuminance Levels (300-3000 lux), Equinox (about between September 22 and March 20), When the sun crosses the celestial equator when day and night are equal in duration. 9 a.m. and 3 p.m.
- **Simulation Option 3:** Illuminance Levels (300-3000 lux, between 9 a.m. and 3 p.m.) [8, LEED, U 2014.

The study indicates that the interior designs of buildings achieve about 5% of natural daylight, and that the ratio of the level of electric lighting to the level of natural lighting is within the limits of 2%, and the preferred percentage ranges between 2% to 5% and the ratio of electric lighting to natural lighting is within the limits of 2%, but less than 1% is considered unacceptable [14].

4. Methodology

The research paper dealt with a case study of a sports building with the aim of improving the visual and thermal properties by improving the quality of lighting and thermal comfort inside the gymnasiums, in addition to saving the energy consumed.

This was done in three steps, including (a theoretical Part - an analytical Part - an applied Part), then producing results that demonstrate the feasibility of the research proposals.

Theoretical Part: The definition includes the required illumination parameters as well as the thermal properties of indoor stadium halls. Learn about phase change materials, including their types and applications.

Analytical Part: Selecting a sports building and conducting an analytical study on its dimensions, facade configuration, and advantages and disadvantages in its current standing position.

Applied Part: The results of Base Case Building measurements (Daylighting, Solar Radiation, thermal performance, and energy consumption rates) are recorded using the simulation program (D.B).

- Use PCM TRANSLUCENT material to improve the performance of DAYLIGHT by selecting opening ratios (openings in the northern façade (WWR%)) that give the best results for daylighting. To improve the performance of thermal properties, the appropriate PCM paraffin RT28HC material is used for thermal insulation of the southern facade, which is most exposed to solar radiation during the day. And re-record the measurements extracted from the simulation program.
- Making comparisons between the results of measurements before and after introducing the modifications, deriving improvement rates in "daylighting", Solar Radiation, thermal performance, and energy consumption, inside Hall sport, and producing the research study results

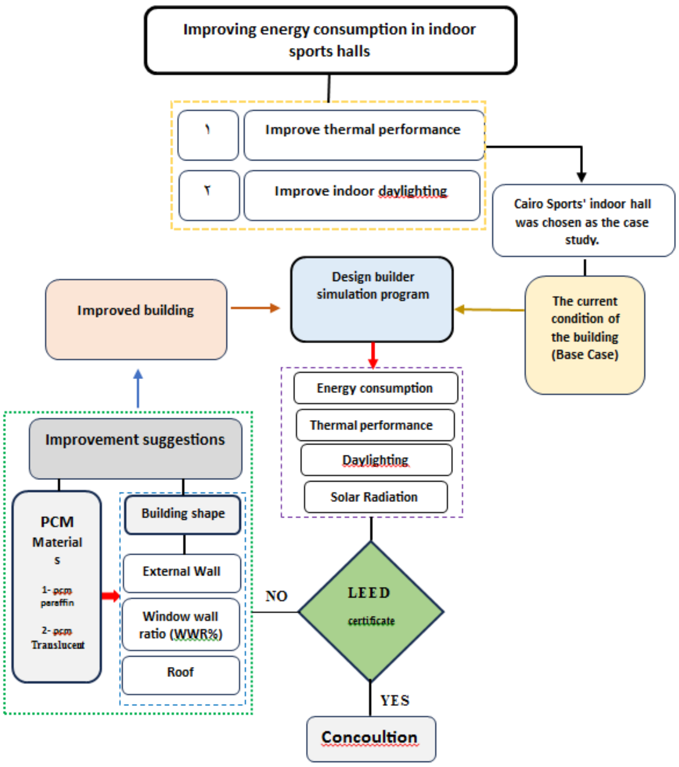


Figure 1. Diagram summary of the Research Methodology, Source: Authors

5. Analytical Part:

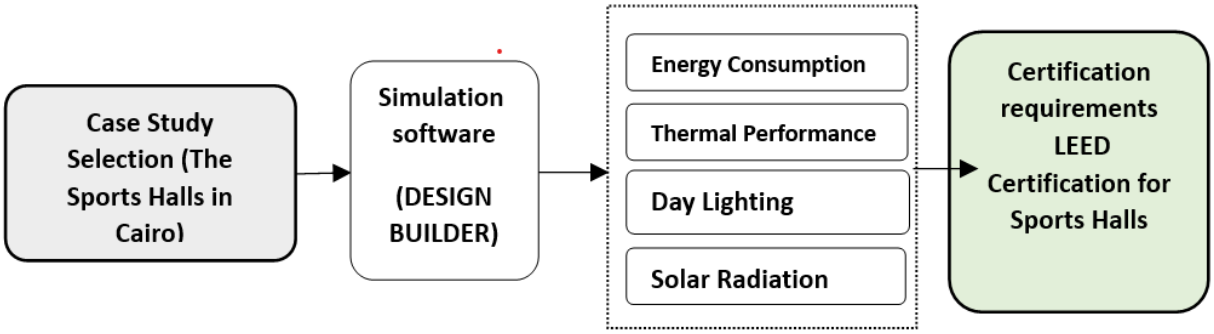


Figure 2. The diagram of the analytical part is shown, Source: Authors

5.1 Case Study (Model definition)

The research focuses on the Arab Contractors Club's sports hall building in Nasr City, Cairo.

The model is a 4740 square meter building with one floor that includes two closed halls, one with an area of 1730 square meters for practicing gymnastics and the other with an area of 2200 square meters for practicing basketball, as well as internal service spaces.

The longest side is approximately 100 m in the northern façade, and it provides natural sunlight during the day due to the presence of windows. The southern façade is solid without openings.

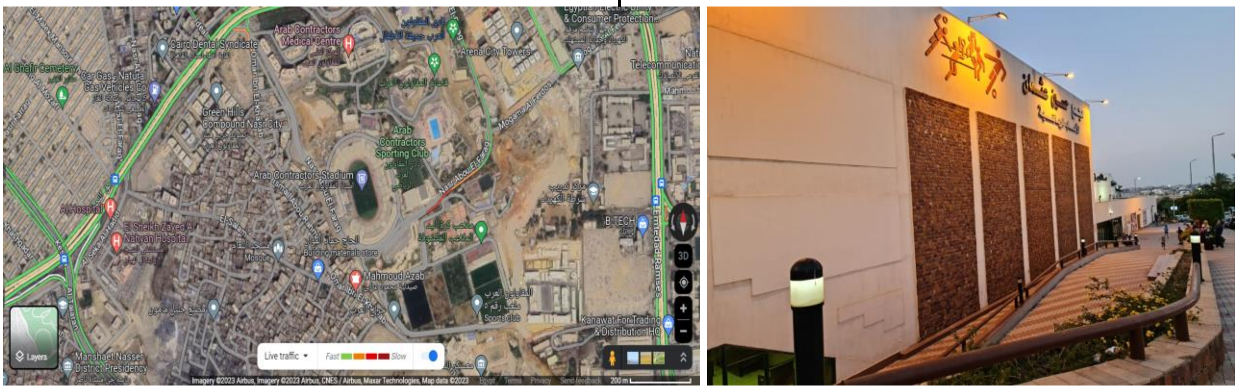


Figure 3. Locations of the Arab Contractors Sporting Club, El-Nasr Road (via Google Earth), source: Authors

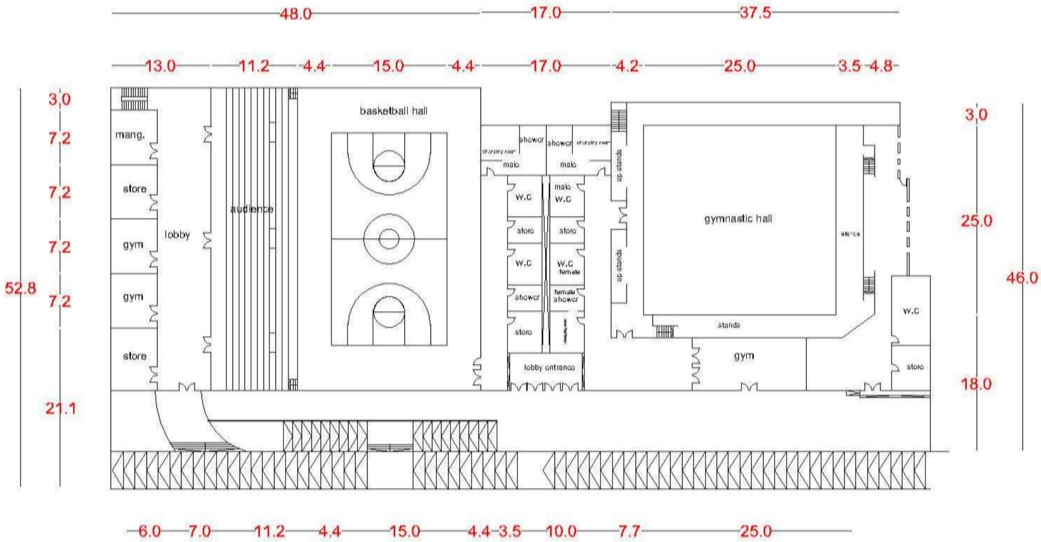


Figure 4 Architecture Plan for the Arab Contractors Sporting Club, Source: Authors

5.2 Climate of the study area:

According to the (Köppen-Geiger) classification, Cairo is located in a desert environment with a dry, hot climate. The average temperature is 14 degrees Celsius in winter (from November to April) and 30 degrees Celsius (from May to October) [15].

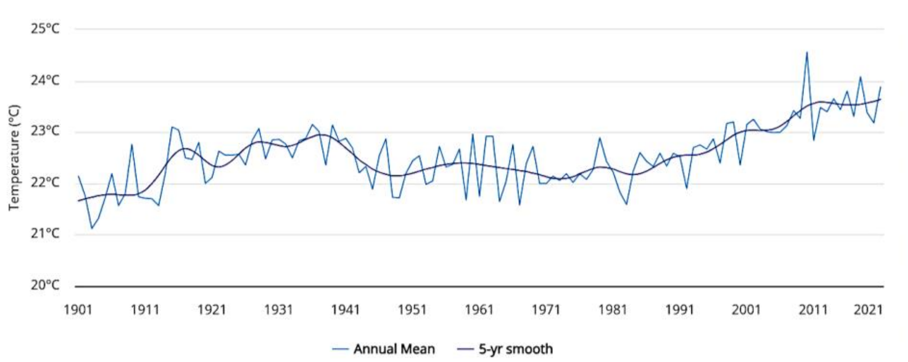


Figure 5. Observed Average Annual Mean Temperature of Egypt for 1901-2021

5.3 SIMULATION INPUT DATA IN THE DESIGN-BUILDER PROGRAM [16].

5-3-1 (Simulation of temperature and relative humidity):

In this part, the results of simulating data on "thermal properties, energy consumption, and daylighting" for the basic condition of the building for the two halls will be studied by entering them into the DESIGN BUILDER program through three tests:

1- The relationship between the operating air temperature and relative humidity over a whole year.
2- The total potential energy used per month during the year.
3- Analysis of the daytime lighting of the hall spaces by analyzing the daylight in the spaces' areas for the daylight factor DF% LUX. The sky was overcast, and the mid-March and mid-August days were chosen as the hottest days of the year. Measurements were made 6 times during the day, each day, with a difference of two hours between each measurement. And the other (8,10,12,14,16,18)

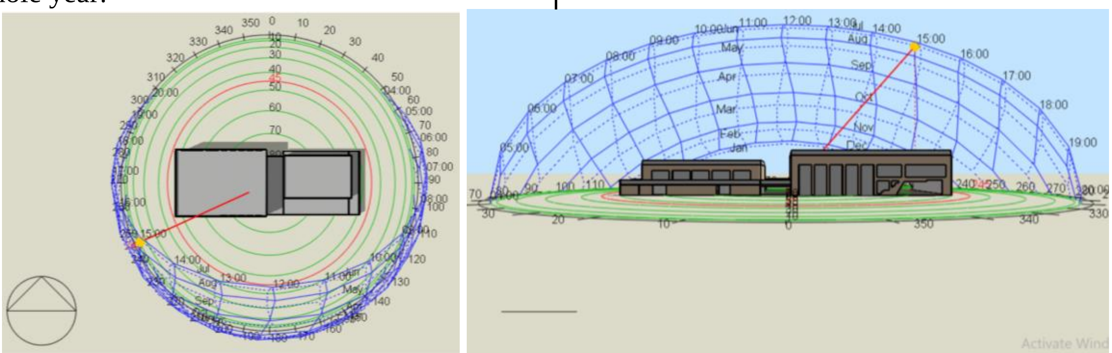


Figure 6: Solar path of the sports hall building, Cairo, Egypt, Source: Design builder by Authors

Table 3: Design Builder Simulation input parameters

Space Dimensions	106 x 38 m2
Simulated Wall Orientation	South
WWR%	25%-35%-45%
Opening Dimensions	3.0 m x 6.0 m
Lighting	Fluorescent
Sport Hall Capacity	Hall 1:40 gymnastic /Hall 2: 40 basket ball
	1.12 person/m2 in normal days
Working Time	For June, July, August and September in summer courses, the occupancy rate is about 1.2 person/m2
	For December and January in winter courses, occupancy rate is about 0.8 person/m2
Annual Holiday	February
HVAC System	
Activities	Fan Coil Units
	Clothing:0.3 clo
	Capacity:1.2
Natural Ventilation	Non

5-3-2 Simulation of total cooling and energy consumption on Base Case Model:

The simulation results show the rate of energy consumption during the months of the year and indicate that the highest rate of consumption occurs in the months of August and July, where the consumption rate reaches 15 kilowatts per hour, as shown Figure (7).

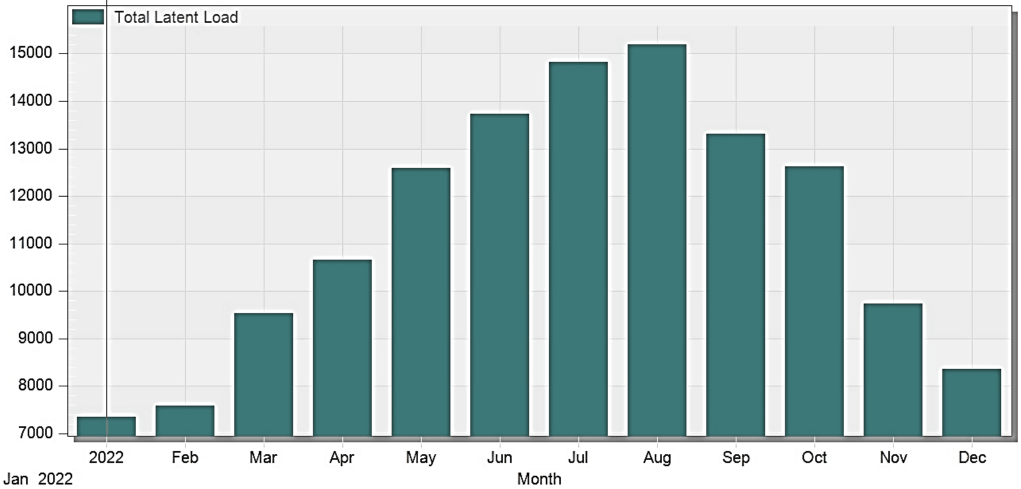


Figure 7: Cooling loads for the Base case, (Design Builder Screen Shot)

5-3-3 Temperature and relative humidity simulation

The results appear as shown in Figure (8), which depicts the relationship between (operating air temperature) and relative humidity for all months of the year. The results show that the highest air temperature reaches 31 degrees Celsius in the month of August, which is the hottest month of the year, and in this month the humidity percentage reaches (RH 57%).

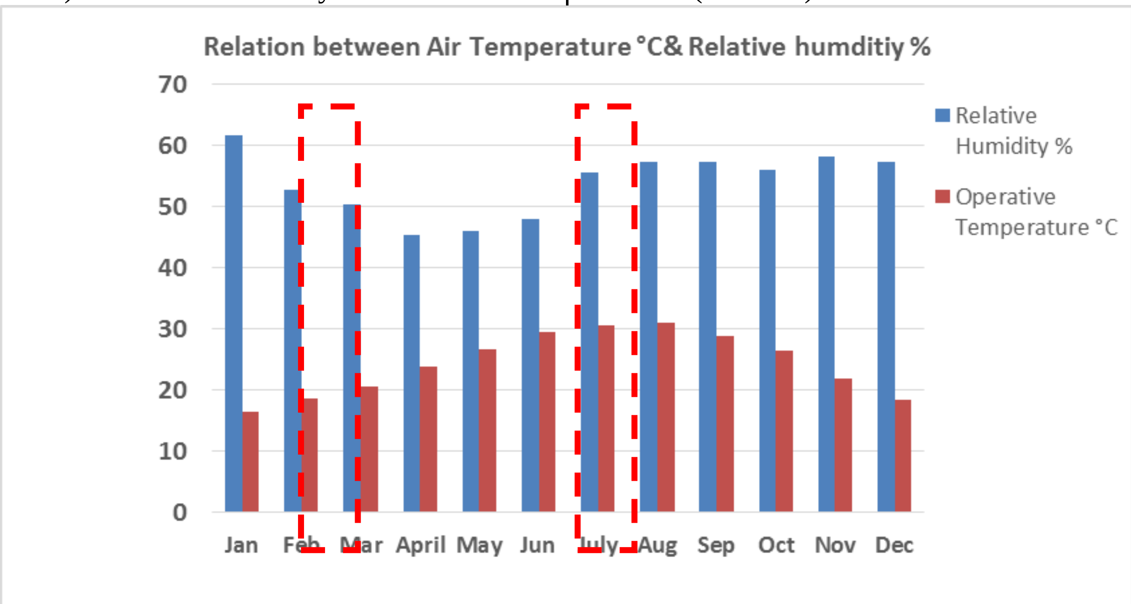
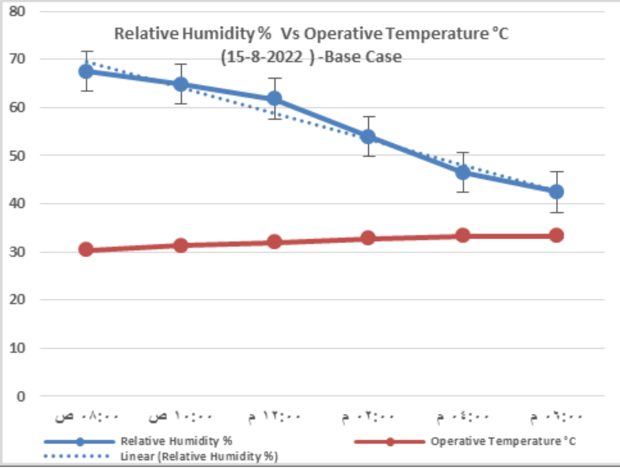


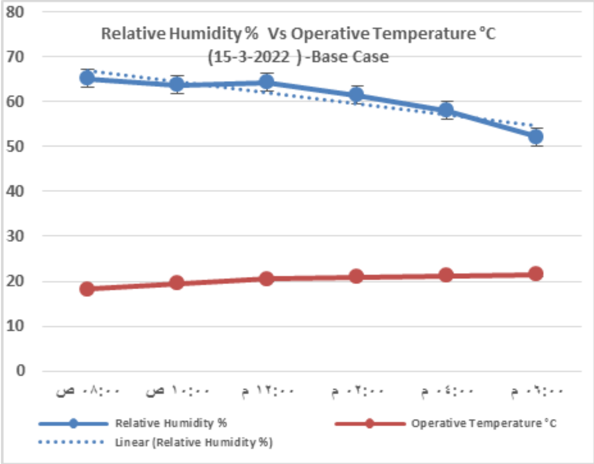
Figure 8: Relation between the Operative air temperature OC and relative humidity % of the Base case

5-3-4 Simulation of operating temperature and relative humidity performance:

Table (4) shows the results of temperature and relative humidity for the first day in mid-August 8/15/2022 at the following times: (8, 10, 12, 14, 16, 18). Around 16 o'clock, the maximum operating temperature is 34 degrees Celsius, and then the relative humidity (RH) is 48%., also shows the temperature and relative humidity results for the second day in mid-March 3/15/2022 for the same hours (8, 10, 12, 14, 16, 18). It shows that the maximum operational temperature reaches 22 degrees Celsius at precisely 16 o'clock, and the relative humidity is 59% RH.

Table 4. The Results of temperature and relative humidity in Base case building on March 15th, and August 15th.





Analysis

According to the graph, the maximum operative air temperature is 34 OC at 4:0 p.m. with 48 % RH.

The graph indicates that at 4.0 p.m., the operational air temperature reached a high of 22 OC and 59% relative humidity.

5.3.5 Simulation of Daylight Illuminance performance and analysis of visual comfort in daylight:

There are Four standards that are most commonly used to measure comfort in indoor daylight through the availability of natural light. "Natural light is daylight that penetrates through walls." These are the daylight factor DF standards - Self-control of daylight - daylight intensity UDI - annual exposure to sunlight.

Table 5. Outputs of the Design-builder Simulation of the Base case.

Daylight Parameters	
Exterior surfaces reflectance	White Ground 0.1
External obstructions	No obstructions
Internal surfaces reflectance	- Walls: 0.5
	- Floors: 0.3
	- Internal obstructions/furniture: 0.7

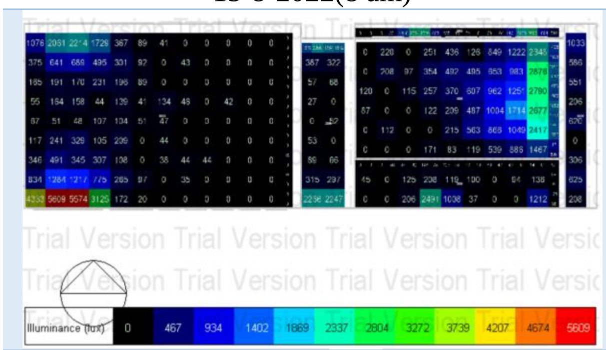
- Simulations are conducted on BASECASE to analyze the current situation in accordance with the LEED version where the sky is overcast, (1000 CIF lux).

Daylighting simulation results in Base Case on August 15th:

Table (6,7) shows the results of simulating indoor daylight for the day on August 15th for times (8,10,12,14,16,18), The daylight self-control system was used to save energy consumption, artificial lighting was avoided, and the daylight system was used, and its scale is UDI It is the unit of daylight that range from 100 to2000 lux/m2.

Table 6. Daylighting illuminance (lux) maps Outputs of the Design-builder Simulation of the different hours of the Base cases on August 15th.

15-8-2022(8 am) 15-8-2022(10 am)



15-8-2022(12 pm) 15-8-2022(14 pm)

15-8-2022(16 pm) 15-8-2022(18 pm)

Table 7. Daylighting illuminance(lux) Grid Outputs of the Design-builder Simulation of the different hours of the Base cases on August 15th.

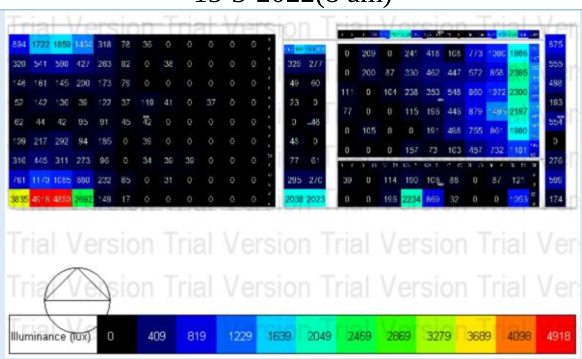
Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 (m2)	8 am	3.555	0	11.59	2876.4
		10 am	2.839	0	10.508	3929.25
		12 pm	2.332	0	8.144	3460.74
		14 pm	4.761	0	6.82	2613.61
		16 pm	2.077	0	6.202	1628.84
		18 pm	2.297	0	6.391	666.98

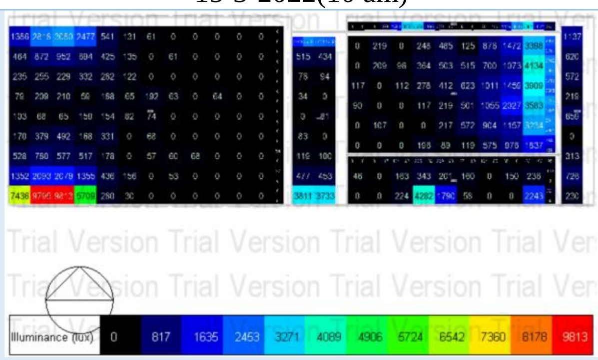
Daylighting simulation results in Base Case on March 15th:

Table (8,9) shows the results of an indoor daylight simulation for the second day, March 15th, 2022, at times (8, 10, 12, 14, 16, 18). The simulation results for the daylight factor are shown in the table, with the average daylight factor being (2.25%), the minimum daylight factor being ZERO, and the highest illumination being (25.32%) in proportion to the floor area m2 (11791.42 LUX).

Table 8. Daylighting illuminance(lux) maps Outputs of the Design-builder Simulation of the different hours of the Base cases on March 15th.

15-3-2022(8 am) 15-3-2022(10 am)





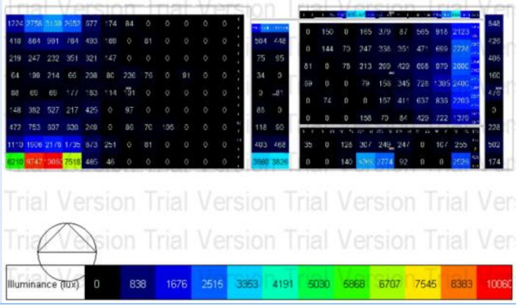
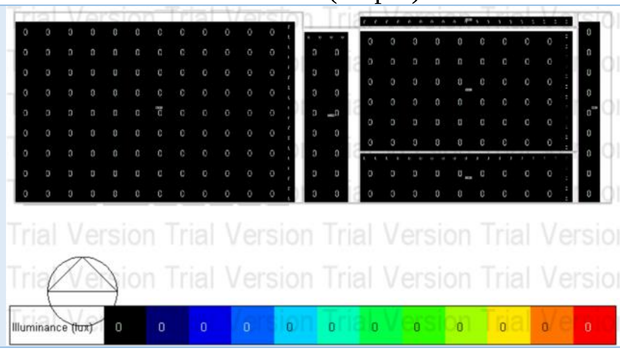
15-3-2022(12 pm)	15-3-2022(14 pm)
	
15-3-2022(16 pm)	15-3-2022(18 pm)
	

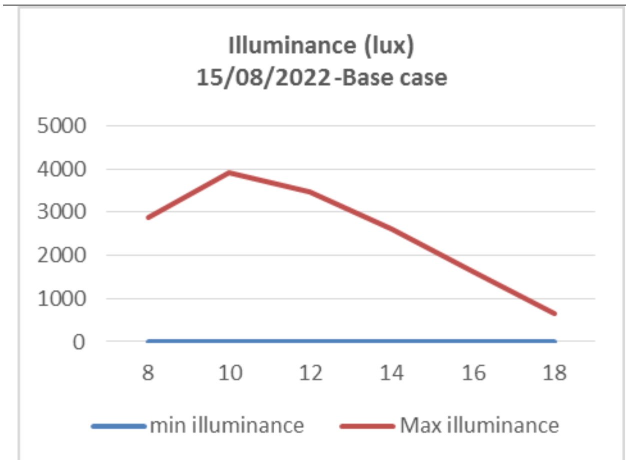
Table 9. Daylighting illuminance (lux) Grid Outputs of the Design-builder Simulation of the different hours of the Base cases on March 15th.

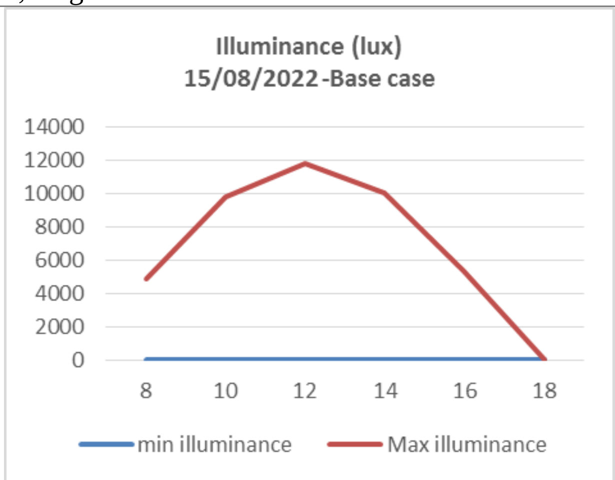
Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 (m2)	8 am	1.849	0	23.563	4918.72
		10 am	2.839	0	25.013	9813.98
		12 pm	2.332	0	25.32	11791.42
		14 pm	2.108	0	24.969	10060.64
		16 pm	2.077	0	23.627	5315.08
		18 pm	2.297	0	0	0

A comparison of the simulation results of the daylighting degree in Base Case:

In the Base Case, a comparison of the simulation results of the maximum and minimum daylighting degree within the sports halls on the 15th of August and 15th of March, as shown in Table (10).

Table 10. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Base Cases on March 15th., August 15th.





5-3-6- Comparison of solar radiation simulation results and their relevance to total latent load, CASE STUDY:

The simulation results that show the relationship between external windows to solar radiation and the total potential loads. According to the graph, the percentage of solar radiation absorbed by the window in August was 16560 kilowatt-hours, and in March it was 8000 kilowatt-hours, and these rates were converted. In August, the temperature within the space reached 9919 kilowatt-hours. And 15,250 kWh in March, Although the amount of sunlight inside the space is tiny, the percentage of energy consumption was high, and these results indicate that the space needs improvement and alteration, as shown Figure (9) .

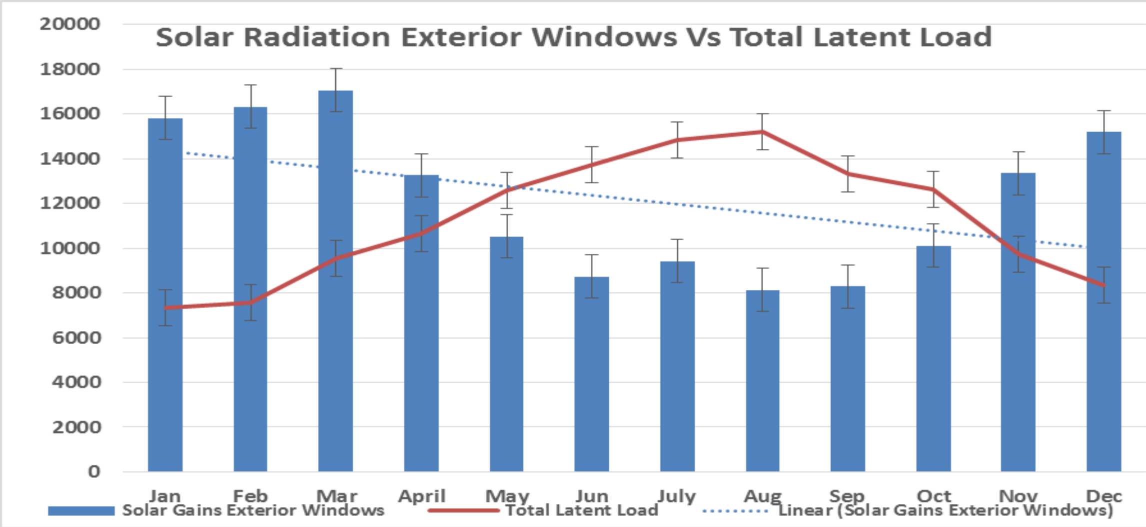


Figure 9: Relation of Solar Radiation exterior window and general lighting of the Base case

5.4 Daylighting Credit - LEED v3 NC 2009 IEQ 8.1

Evaluation of the results of measurements of the degrees of illumination and thermal performance of the SPACES of the basic case according to the LEED system

According to the simulation results of the performance of "thermal performance, daylighting, solar radiation, and energy consumption" for the basic condition of the two halls under study, the research prepared a report on "a statement of the building's eligibility to obtain the LEED v3 daylighting IEQ 8.1 certificate or not, as the approval of the eligibility depends on whether the daylight factor achieves a degree greater than the minimum limit stipulated in this system."

Figure (10) shows that daylight illumination is insufficient for a hall with a 15% occupied area in the presence of areas with a lighting of 10-500/ft3. The RADIANCE simulation program was used to arrive at the results, which gives detailed estimations of the illumination levels throughout the building. The results of the LEED certification report indicated that the current situation of the base case sports halls in terms of daylighting is unacceptable.

Daylighting data	
Project file	Arab Contractors Sporting Club
Report generation time	30/07/2023 14:43:34
Sky model	1-Standard sky, 2-CIE clear day
Time 1	9:00, 21 Sep
Time 2	15:00, 21 Sep
Location	Copy of CAIRO AIRPORT
Working plane height (m)	0.750
Max Grid Size (m)	4.000
Min Grid Size (m)	3.000
Illuminance lower threshold (lux)	250.000
Illuminance upper threshold (lux)	10000000.000

Summary Results	
Total area (m2)	4016.2
Total area meeting requirements (m2)	759.8
% Area within illuminance threshold limits	18.9
LEED v3 NC 2009 IEQ 8.1 Status	**FAIL**

Figure 10 LEED v2 IEQ 8.1 credits Generate documentation of the base case (Design Builder Screen Shot).

6. Application Part:

Proposals for improvements to daylight performance, solar radiation, thermal performance, and energy consumption, as shown in Figure (11)

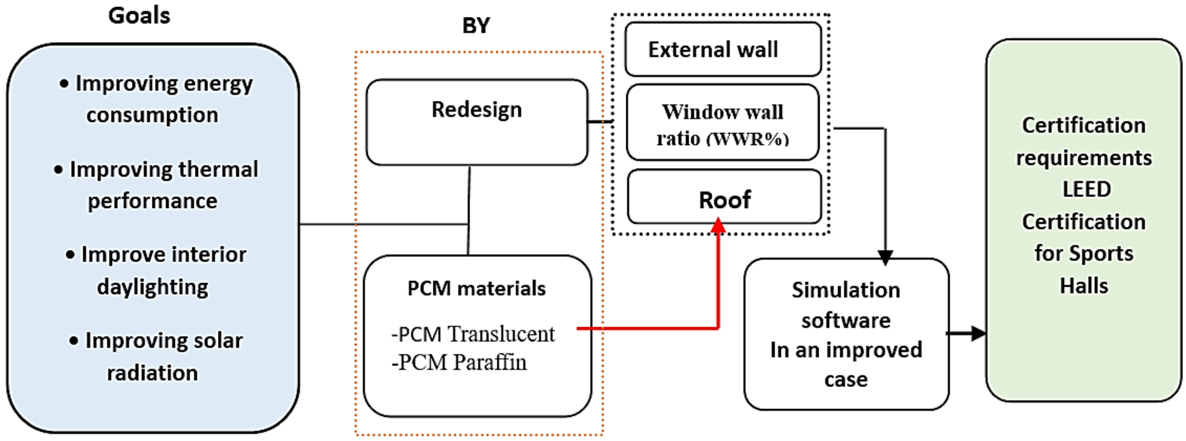


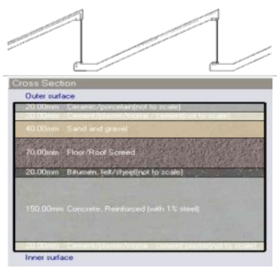
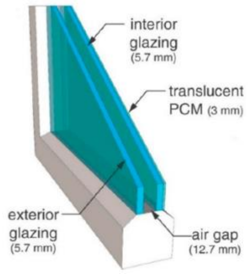
Figure 11 shows a proposed strategy for improving thermal performance and daylighting in a sports hall in the Applicable part, source: Authors

6.1 First, improving thermal performance by:
Using thermal insulation to improve thermal performance by using phase change materials (PCM paraffin RT28HC) as a heat-insulating material inside the sports hall.

6-2 Second, improve daylight by:
Presenting improvement suggestions necessitates conducting experiments using different window wall ratio (WWR%) proportions and choosing many types of glazing and thermal insulation materials to discover the appropriate proportions and materials that achieve the goals through:

1- Increasing the space of window wall ratio (WWR%) in facade walls suited for receiving useful natural light.
2- Use a suitable PCM translucent material for glazing and another for external wall thermal insulation.
3- It is suggested that the ceiling be designed with a saw-toothed sky court system facing north, which reduces glare and increases the window wall ratio (WWR%) of apertures for natural light (daylighting) to increase the entry of natural light (daylight) entering the sports hall space.

Table 10. The proposed Roof, Wall, and Glazing types of improving strategies (Design-builder).

PCM-Roof	PCM-External Wall	PCM-Internal Partition
		
• **0.001 cm Metal sheet roofing zinc** • **0.01 Bio-PCM, saw-toothed sky court system**	• 0.01 cm Cement Sand • 0.01 cm Bio-PCM • 0.1 cm Concrete block, 0.01 cm cement /sand/mortar	• Exterior glazing (single glazing) • Translucent -PCM 5mm • Interior glazing

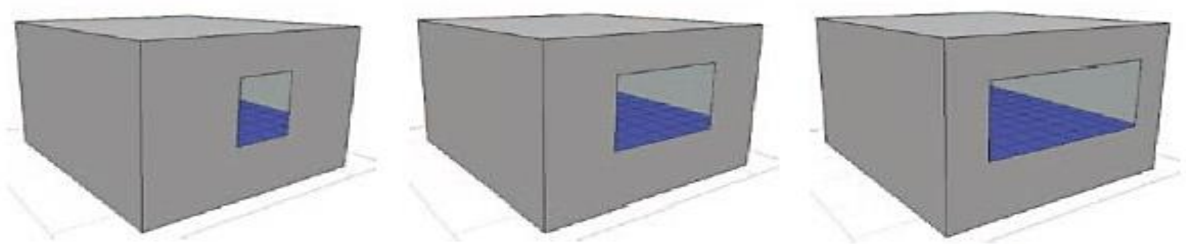


Figure 12 Window Wall Ratio (WWR%) of the study, Improved cases

Figure 13 Interior view of the sports hall, source: Authors

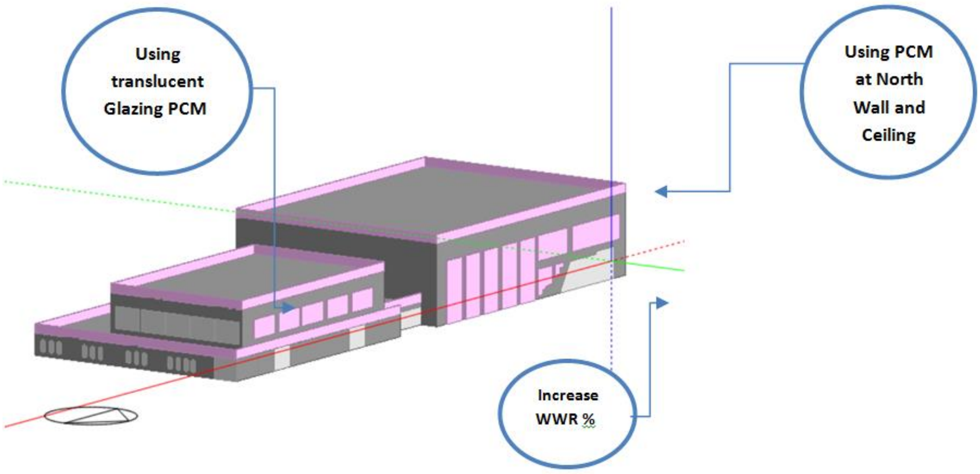


Figure 14 Treatment Methods used in the base case model, source: Authors

6-1 First, improving thermal performance (The results of simulating temperatures and humidity levels after improving window wall ratio (WWR%) and using a phase change material (PCM paraffin RT28HC) as a heat-insulating material inside the sports hall):

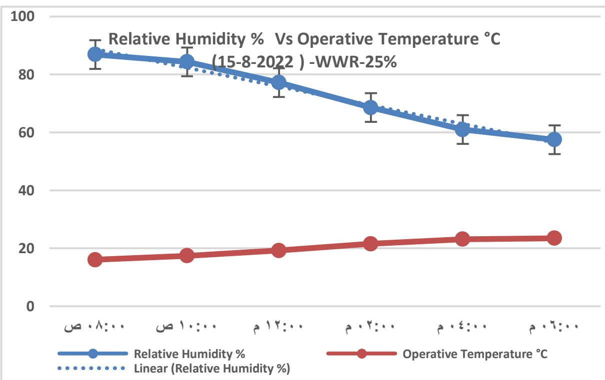
A) The Window Wall Ratio is 25% between the 15th of August and the 15th of March, where the value of cooling loads is the maximum degree of six readings during daylight hours (8 am, 10 am, 12 pm, 14 pm,16pm,18pm), as shown table (12).

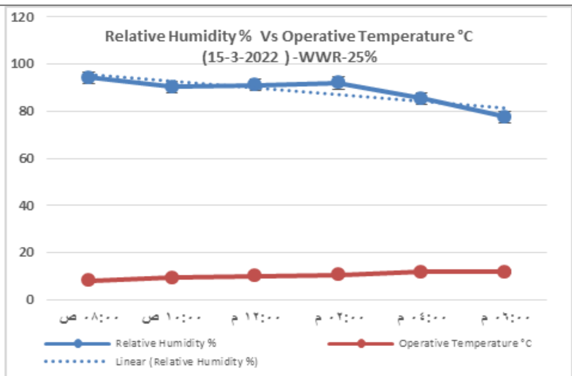
- The Results of the 15th August simulation of temperatures and relative humidity during daylight hours for sports halls after adjustment, show that the best operating air temperature is (23◦C) at six o'clock in the evening, and the relative humidity is (58%).

- The Results of the 15th March simulation of temperatures and relative humidity during daylight hours for sports halls after adjustment, show that the best operating air temperature is (19◦C) at six o'clock in the evening, and the relative humidity is (99%).

Table 12. results of temperature and relative humidity of the Design-builder Simulation of the different hours of the improving cases with 25 WWR% on 15th August, and 15th March

Improved model-WWR 25%





Analysis

The graph indicates that the optimal operating temperature of the air is 23 OC (6:0 pm) with 58 % Relative humidity.	The graph shows that at 6:00 pm with a 99% RH, the highest operating air temperature is 19 OC.

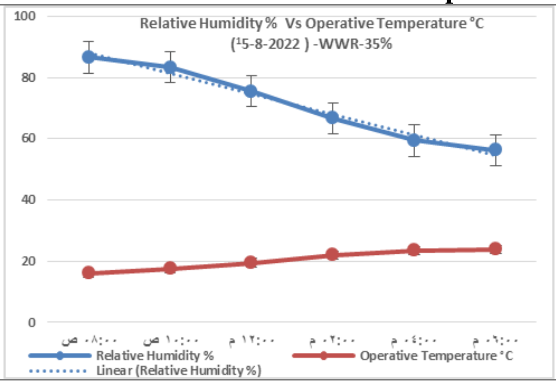
B) The Window Wall Ratio is 35% between the 15th of August and the 15th of March, where the value of cooling loads is the maximum degree of six readings during daylight hours (8 am, 10 am, 12 pm, 14 pm,16pm,18pm), as shown table (13).

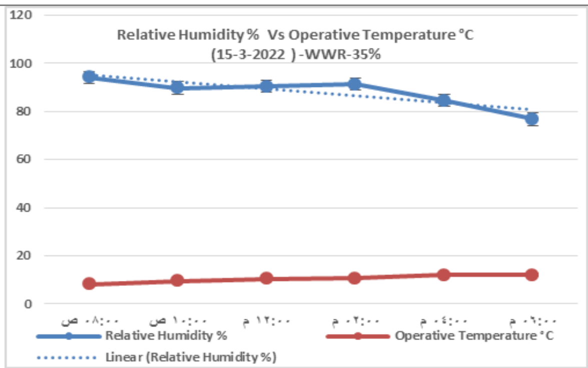
- The Results of the 15th August simulation of temperatures and relative humidity during daylight hours for sports halls after adjustment, show that the best operating air temperature is (22◦C) at six o'clock in the evening, and the relative humidity is (58%).

- The Results of the 15th March simulation of temperatures and relative humidity during daylight hours for sports halls after adjustment, show that the best operating air temperature is (17◦C) at six o'clock in the evening, and the relative humidity is (78%).

Table 13. results of temperature and relative humidity of the Design-builder Simulation of the different hours of the improving cases with 35 WWR% on 15th August, and 15th March.

Improved model-WWR 35%





Analysis

According to the graph, the adaptation of the retrofitted strategies, the maximum operative air temperature is 22 OC at 6:0 pm with 58 % RH.	According to the graph, the maximum operational air temperature at 6:0 pm with 78% RH for the winter session of the retrofitting strategies is 17 OC.

C) The Window Wall Ratio is 45% between the 15th of August and the 15th of March, where the value of cooling loads is the maximum degree of six readings during daylight hours (8 am, 10 am, 12 pm, 14 pm,16pm,18pm), as shown table (14).

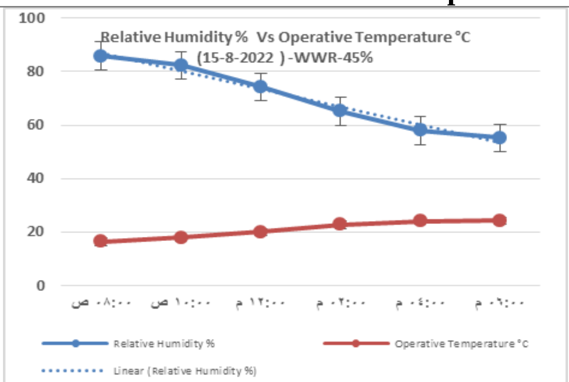
- The Results of the 15th August simulation of temperatures and relative humidity during daylight hours for sports halls after adjustment, show that the best operating air temperature is (20◦C) at six o'clock in the evening, and the relative humidity is (56%).

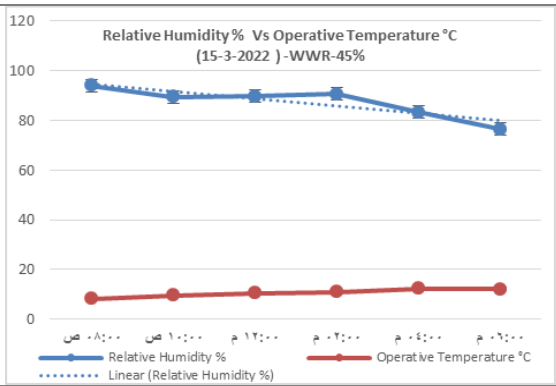
- The Results of the 15th March simulation of temperatures and relative humidity during daylight hours for sports halls after adjustment, show that the best operating air temperature is (16◦C) at six o'clock in the evening, and the relative humidity is (72%).

By comparing the simulation results for the selected ratios, we can clearly see that the window wall ratio exceeds 45% in the degrees of improvement of the thermal characteristics of temperature and relative humidity of the two sports halls.

Table 14 Results of temperature and relative humidity of the Design-builder Simulation of the different hours of the improving cases with 45 WWR% on 15th August, and 15th March.

Improved model-WWR 45%





Analysis

The graph indicates that the optimal operative air temperature is 20 OC (6:0 pm) on 15th August with 56% Relative humidity.	According to the graph, the adaptation of the retrofitted strategies at the winter session, the maximum operative air temperature is 16 OC at (6:0 pm) with 72 % RH.

6.2. Simulation Results for Daylighting

- First: Improving daylight:

Experiments were conducted to obtain simulation results showing the best percentage of space in the walls. The data was recorded for percentages of openings WWR% (25%, 35%, 45%, 55%), and the best percentage was 45%, where the percentage of lighting improvement reached 163%. When the percentage exceeds 45%, Glare issues with daylight start appearing.

- Second: Choosing the glazing material:

Traditional glazing leads to a 15% reduction in energy consumption due to its effect on the indoor air temperature and also affects thermal comfort and natural daylighting performance. The PCM material stores energy as much as 14 times the traditional materials, so it was chosen to replace the existing single glass in the basic case of the building.

- Third: Roof design:

The researcher used the sky court to improve natural lighting and thermal performance by adding an area for daylight to penetrate by equipping the roof with a sawtooth-shaped roof aperture (sky court).

6-2-1 Results of an indoor hall sports daylight simulation. It is proposed to increase the window wall ratios and to utilize the transparent phase change material (PCM TRANSLUCENT), According to the LEED certification evaluation

A) The Window Wall Ratio is 25% between the 15th of August and the 15th of March, when the cooling load value is at its peak for six hours of daylight readings (8 a.m., 10 a.m., 12 p.m., 14 p.m., 16 p.m., and 18 p.m.).

- The Results of the 15th August simulation daylight hours for sports halls after modification are shown in Table (15), which reveals that the average daylight factor is (7.744%), the minimum daylight factor is (1.055%), the highest daylight factor is (15.75%), and the maximum illuminance is (lux). In terms of floor space (5422lux).

Table 15. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Improved cases with 25 WWR% on 15 August

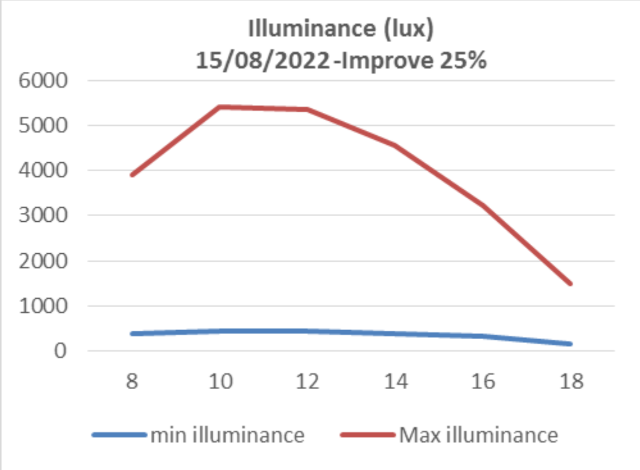
Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 (m2)	8 am	8.804	1.573	15.758	3915.05
		10 am	7.492	1.145	14.504	5422.45
		12 pm	6.882	1.053	12.615	5352.78
		14 pm	6.843	1.069	11.907	4549.2
		16 pm	7.449	1.205	12.365	3238.43
		18 pm	8.997	1.479	14.28	1490.14

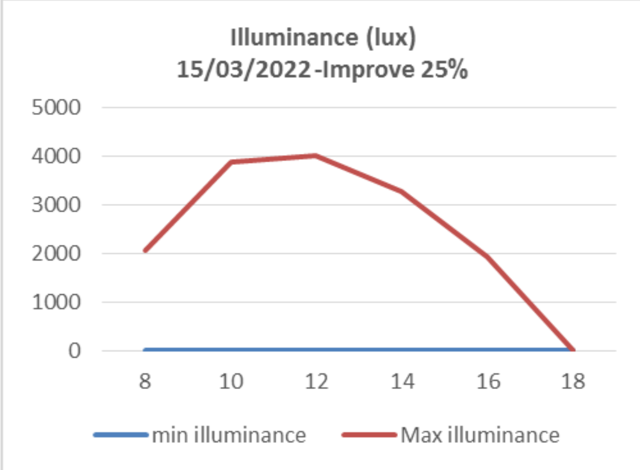
The Results of the 15th March simulation daytime hours for sports hall following the amendment proposal, revealed that the average daylight factor is (5.3%), the minimum daylight factor is (0%), and the maximum is (15.54%), and the maximum is (lux). In terms of the floor area (4004.38 lux), as shown in Table (16)

Table 16. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Improved cases with 25 WWR% on 15 March.

Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 m2)	8 am	6.633	0	15.541	2058.02
		10 am	5.53	0	14.721	3869.38
		12 pm	4.87	0	12.63	4004.38
		14 pm	4.761	0	11.781	3265.03
		16 pm	5.187	0	12.243	1926.42
		18 pm	0	0	0	0

Table 17. Comparison of maximum and minimum daylight results for two days, August 15th and March 15th, for the window wall ratio 25% (WWR%)





B) The results in the Window Wall Ratio are 35% between the 15th of August and the 15th of March for daylight hours (8 am, 10 am, 12 pm, 14pm, 16 pm, and 18 pm).

- **The results of the 15th August** simulation showed that the average daylight factor is (8.615%), the minimum daylight factor is (1.302%), the maximum is (16.57%), and the maximum illuminance is (5632.2 lux), as shown in Table (18).

Table 18. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Improved cases with 35 WWR% on 15 of August.

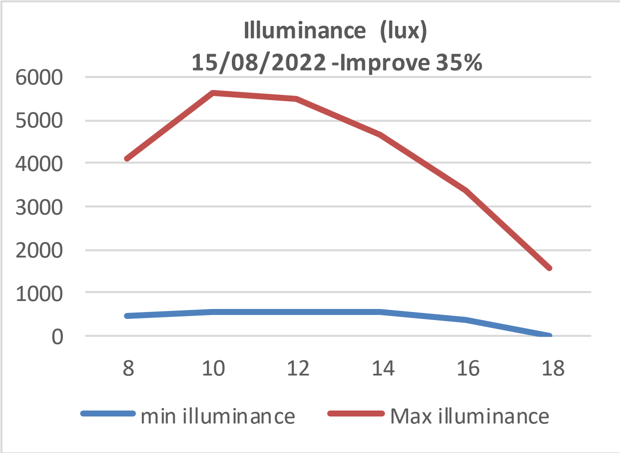
Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 m2)	8 am	9.807	1.845	16.57	4122.14
		10 am	8.344	1.451	15.079	5632.21
		12 pm	7.63	1.305	12.947	5503.78
		14 pm	7.59	1.302	12.255	4686.71
		16 pm	8.294	1.445	12.792	3352.9
		18 pm	10.028	1.776	14.976	1563.81

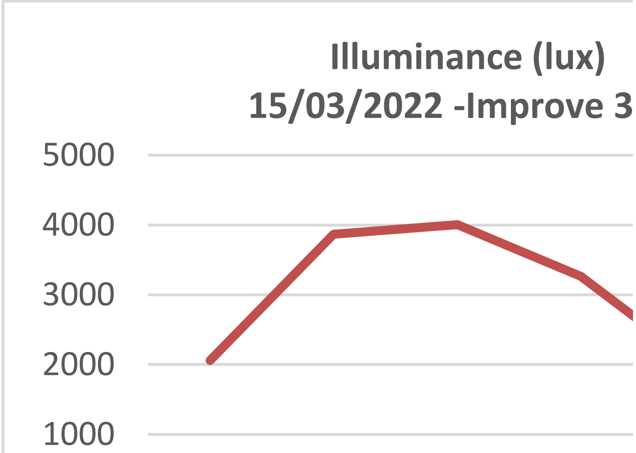
The results of the simulation on 15th March showed that the average daylight factor is (5.801%), the minimum daylight factor was (1.359%), the maximum daylight factor was (16.203%), and the maximum illumination was (4091.1 lux), as shown in Table (19)

Table 19. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Improved cases with 35 WWR% on 15 March.

Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 47400 (m2)	8 am	7.122	1.979	16.203	2151.23
		10 am	5.969	1.529	15.136	3969.37
		12 pm	5.237	1.359	12.886	4091.1
		14 pm	5.115	1.369	12.109	3360.41
		16 pm	5.561	1.545	12.678	1998.95
		18 pm	0	0	0	0

Table 20. Comparison of maximum and minimum daylight results for two days, August 15th and March 15th, for the window wall ratio 35% (WWR%)





C) The results in the Window Wall Ratio are 45% between the 15th of August and the 15th of March for daylight hours (8 am, 10 am, 12 pm, 14 pm, 16 pm, and 18 pm).

- The results of the 15th August simulation showed that the average daylight factor is (25.653%), the minimum daylight is (5.576%), the maximum is (22.64%), and the maximum is (8668.24 lux), as shown in Table (21, 22)

Table 21. Daylighting maps Outputs of the Design-builder Simulation of the different hours of the Improved cases with 45 WWR% on 15th August.

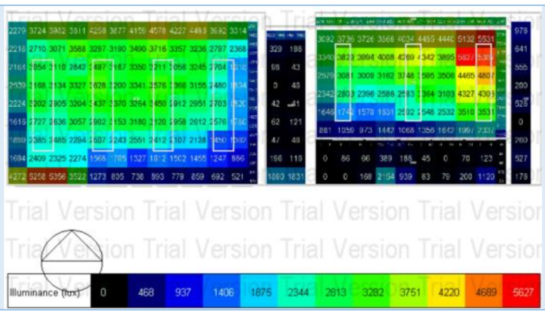
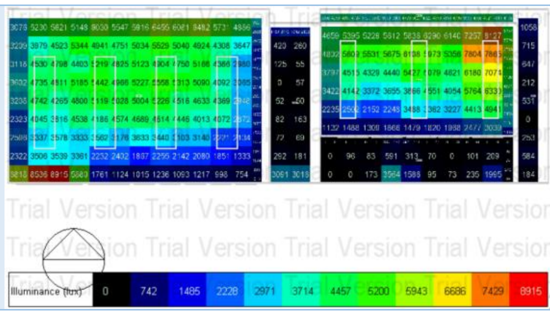
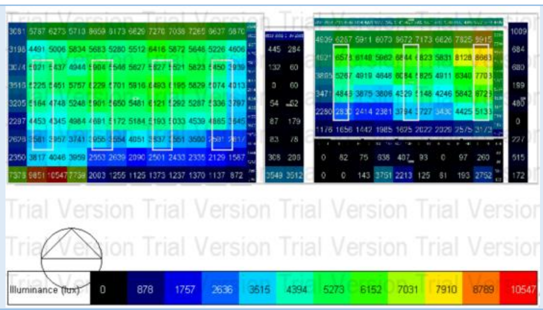
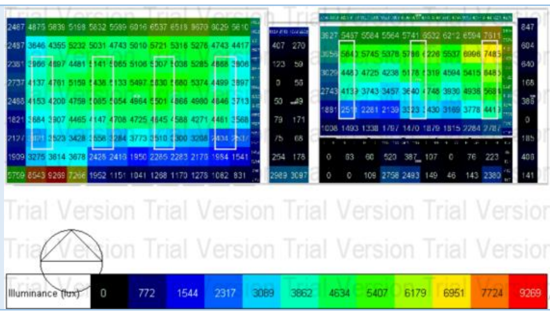
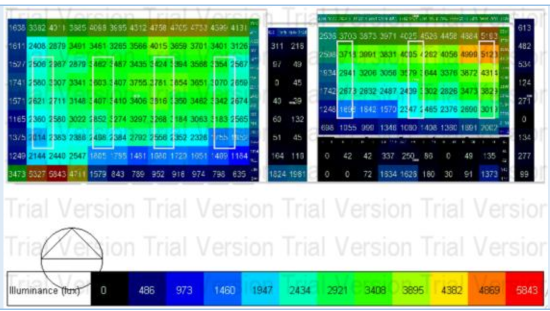
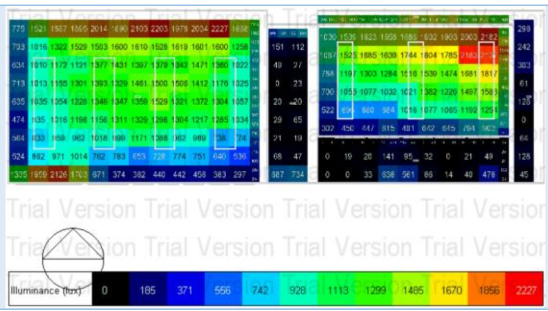
15-8-2022(8 am)	**15-8-2022(10 am)**
	
15-8-2022(12 pm)	15-8-2022(14 pm)
	
15-8-2022(16 pm)	15-8-2022(18 pm)
	

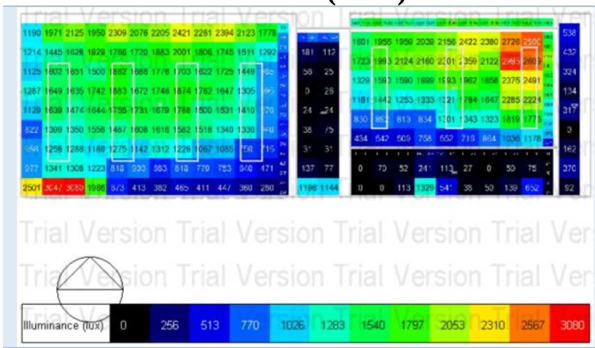
Table 22. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Improved cases with 45 WWR% on 15 August.

Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 (m2)	8 am	34.57	6.319	22.64	5627.7
		10 am	23.688	5.728	20.934	7865.07
		12 pm	23.268	5.595	20.367	8668.24
		14 pm	23.084	5.576	19.509	7485.63
		16 pm	23.293	5.984	19.517	5123.26
		18 pm	24.381	6.519	20.914	2183.83

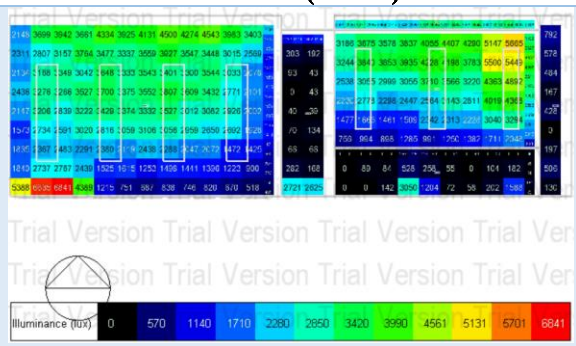
The results of the 15th March simulation showed that the average daylight factor is (8.626%), the minimum daylight is (8.735%), the maximum is (27.389%), and the maximum illumination is (6841.62 lux). as shown in Table (23,24).

Table 23 Daylighting maps Outputs of the Design-builder Simulation of the different hours of the Improved cases with 45 WWR% on 15 of March

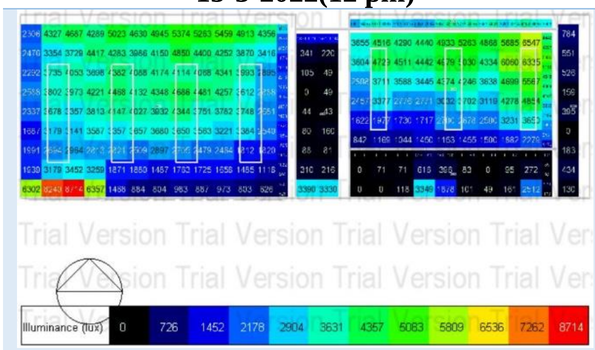
15-3-2022(8 am)



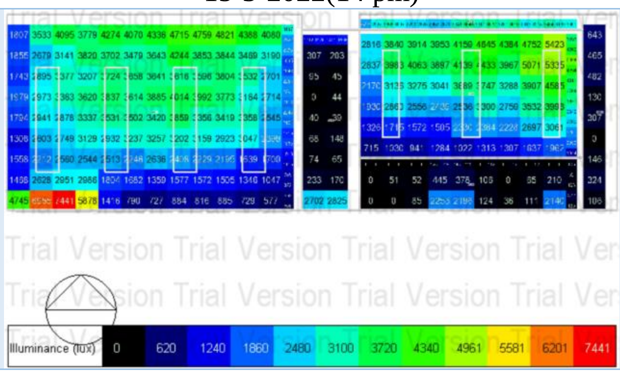
15-3-2022(10 am)



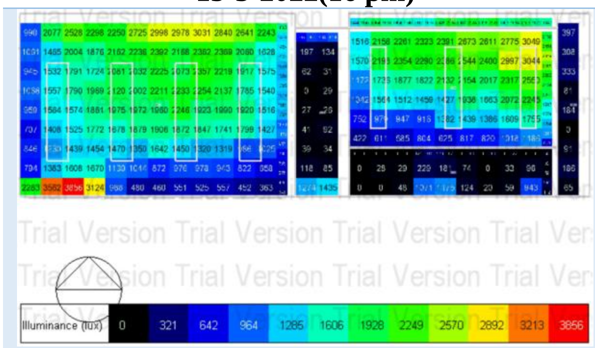
15-3-2022(12 pm)



15-3-2022(14 pm)



15-3-2022(16 pm)



15-3-2022(18 pm)

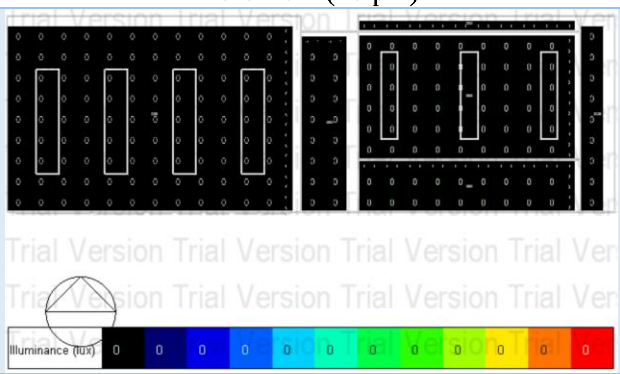
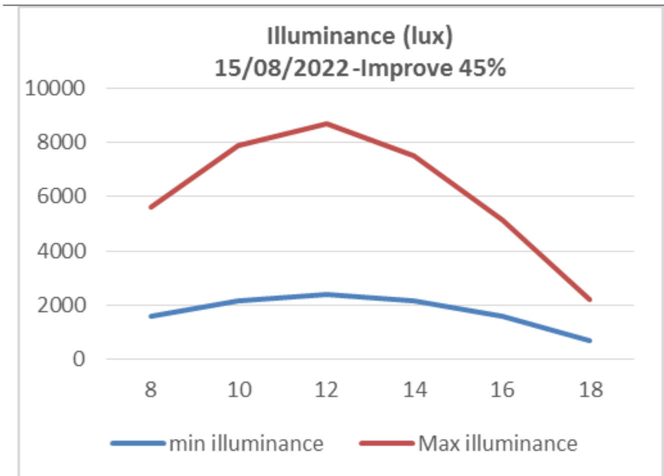
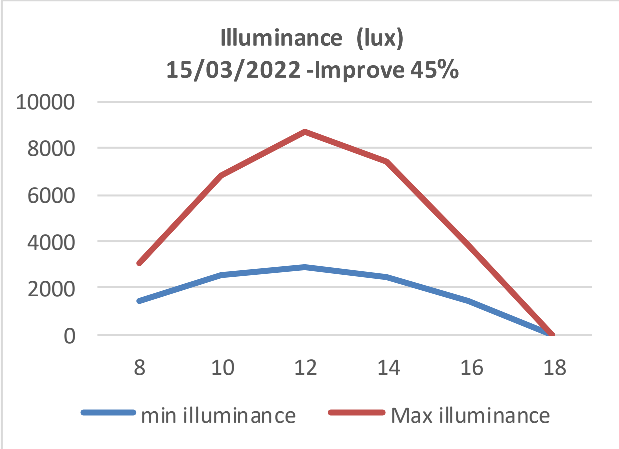


Table 24. Daylighting Grid Outputs of the Design-builder Simulation of the different hours of the Improved cases with 45 WWR% on 15 of March.

Block	Floor Area (m2)	Time/hour	Average Daylight Factor (%)	Minimum Daylight Factor (%)	Maximum Daylight Factor (%)	Max Illuminance (lux)
Total	Gymnastics Hall + Basketball Hall 4740 (m2)	8 am	8.961	10.725	23.296	3080.97
		10 am	8.641	9.691	26.035	6841.62
		12 pm	8.503	9.124	27.389	8714.81
		14 pm	8.424	8.735	26.692	7441.68
		16 pm	8.599	9.15	24.446	3856.32
		18 pm	0	0	0	0

Table 25 Comparison of maximum and minimum daylight results for two days, August 15th and March 15th, for the window wall ratio 45% (WWR%)





By comparing the simulation results for the selected ratios, we can clearly see that the window wall ratio exceeds 45% in the degrees of improvement of the daylighting degree of the two sports halls.

6-3- Daylighting Credit - LEED v3 NC 2009 IEQ 8.1

Evaluation of the results of lighting degree measurements for the spaces of the two sports halls following LEED standard adjustment

To get LEED certified, the sports facility has to illuminate daylight (75%) of the operating area with a sufficient degree of illumination. The results shown in Figure (15) were determined by RADIANCE Simulation, and the results showed that the lighting measurements for the two sports halls after the improvement met the specifications of LEED V3 standards in terms of providing light day inside.

Daylighting data	
Project file	Arab Contractors Sporting Club
Report generation time	30/07/2023 14:32:21
Sky model	1-Standard sky, 2-CIE clear day
Time 1	9:00, 21 Sep
Time 2	15:00, 21 Sep
Location	LONDON/GATWICK ARPT
Working plane height (m)	0.750
Max Grid Size (m)	4.000
Min Grid Size (m)	3.000
Illuminance lower threshold (lux)	110.000
Illuminance upper threshold (lux)	5400.000

Summary Results	
Total area (m2)	4016.2
Total area meeting requirements (m2)	3302.8
% Area within illuminance threshold limits	82.2
LEED v3 NC 2009 IEQ 8.1 Status	PASS

Figure 15: LEED v2 IEQ 8.1 credits Generates documentation of the Improved case (Design Builder Screen Shot).

7. RESULTS

7.1 Comparing the rate of energy consumption inside the halls in the basic and improved cases

Figure (16) shows the rate of energy consumption inside the halls for the Base Case and improved cases, where the rate of energy consumption was reduced by 158% on August 15th (15,000 kwt to 5,800 kwt) and by 92% on March 15th (9,200 kwt to 2,500 kwt).

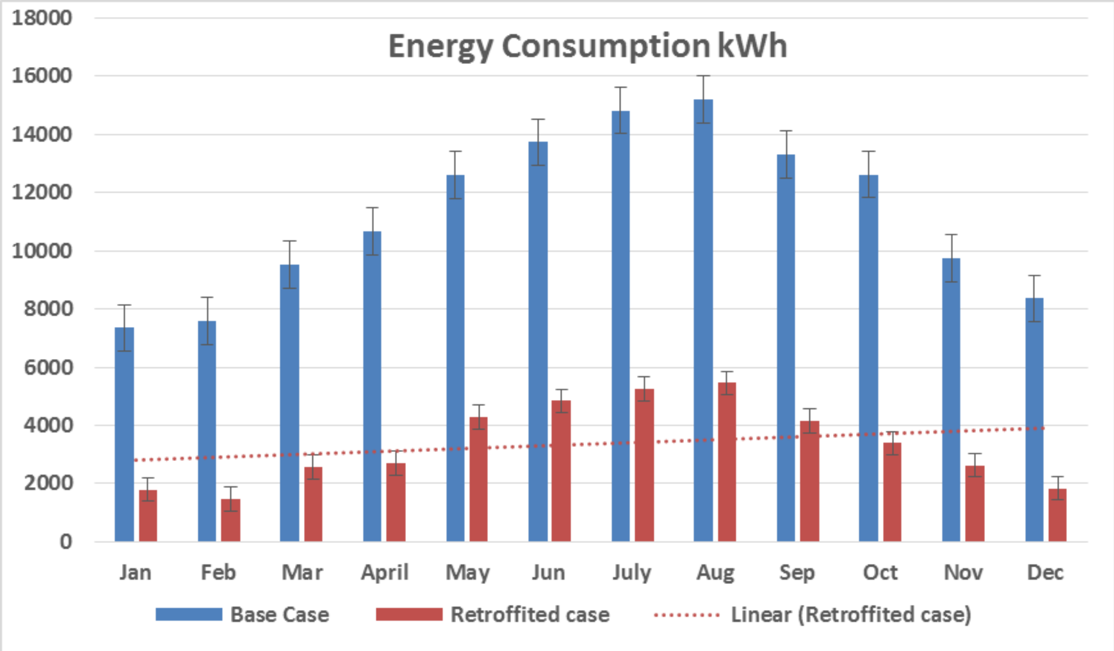


Figure 16: Comparison of the operative air temperature OC for the base case and Improved case

7.2 Results of comparisons (Temperature) between Base Case measures and their measurements after the proposed Improvements:

Comparisons are made between the simulation results of the base case and their results after introducing the proposed improvement of increasing the percentage of openings in the walls and ceiling (WWR%) to 45% of the surface area of the northern façade and the ceiling because this ratio produced the best results for daylighting inside the sports halls when a transparent phase change material (PCM Translucent) was used.

The usage of paraffin phase change material (PCM) to insulate the southern facade and roof walls, with the following comparisons:

Comparison of the working air temperature in the Base Case and that in the improved Case:

Figure (17) shows the operating temperatures for the basic case and its temperature for the improved case for all months of the year, we find that the temperature measurement on August 15th Improved from 31◦C to 27◦C by 13%, and the temperature measurement on March 15th improved from 22◦C to 19◦C by 14%, based on what was selected from the months of August and March during the research.

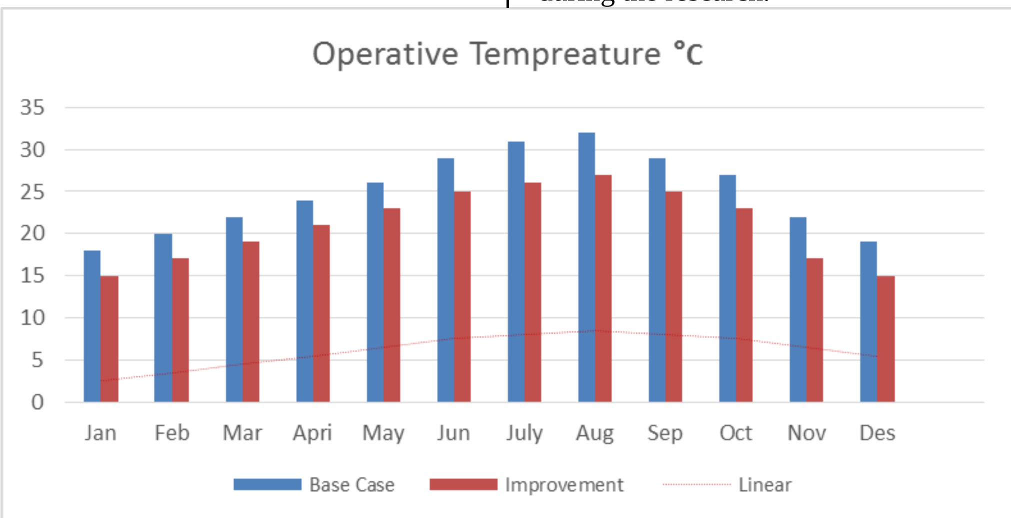


Figure 17: Comparison of the operative air temperature OC for the base case and Improved case

7.3 Comparing the level of natural lighting within the halls before and after improvement:

Figure (18) shows the maximum illumination within the halls for the basic and improved cases during daylight hours, where it increased by (227%, 214%, 186%, 150%, 100%, and 95%) at times (8, 10, 12, 14, 16, and 18).

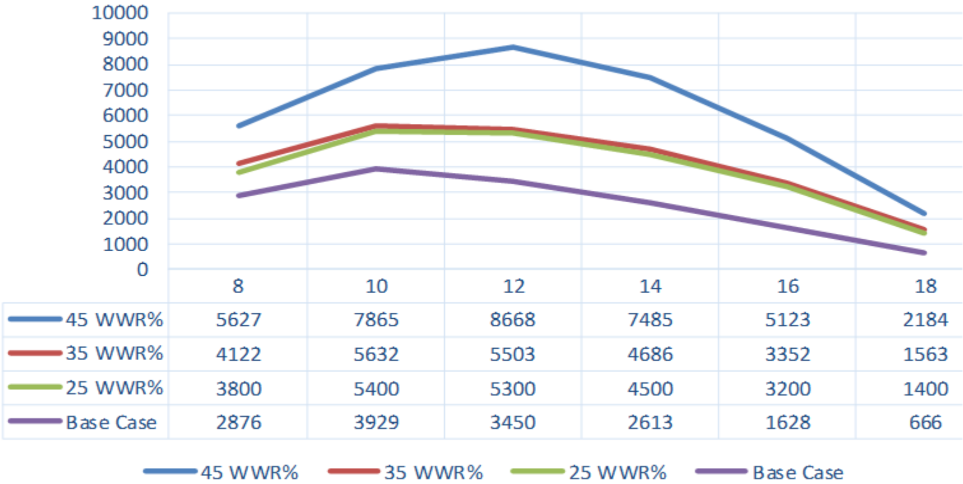


Figure 18: Comparison of the Max Illuminance(lux) graph for the base case and Improved case

7.4 Simulating solar radiation performance and comparing it to the total latent energy loads of the basic case after improvement:

Results of simulation after increasing the window wall ratio (WWR%) in the walls and ceiling. Three suggestions with phase change materials (PCM) suited for glazing and thermal insulation to choose the best (25%, 35%, 45%). The relationship between solar energy and the three percentages of total latent load inside the sports halls is shown in Table (26)

The acquired solar radiation rate of three percentages (WWR%) increases throughout the year, beginning low in January and continuing to increase in the three percentages (25%, 35%, 45%) until it reaches its maximum levels in May and then starts to decrease. As shown in (Figure 19), it decreases gradually until it reaches its lowest level in December.

Figure (19) depicts the total latent loads during the year, as they begin low at the start of the year (January 1600 kilowatts per hour) and gradually increase until they reach their maximum (5800 kilowatts per hour) in August, then gradually decrease until they reach their lowest (1500 kilowatts/hour) in December.

Table 26 compares "solar radiation performance and its relationship with total latent loads for the three cases (WWR%), During the months of August and March".

Statement		WWR (25%)	WWR (35%)	WWR (45%)
Solar radiation	March	9000	11000	16500
	August	14000	175000	26500
Total latent load	March	2500	2700	2900
	August	5000	5300	5500

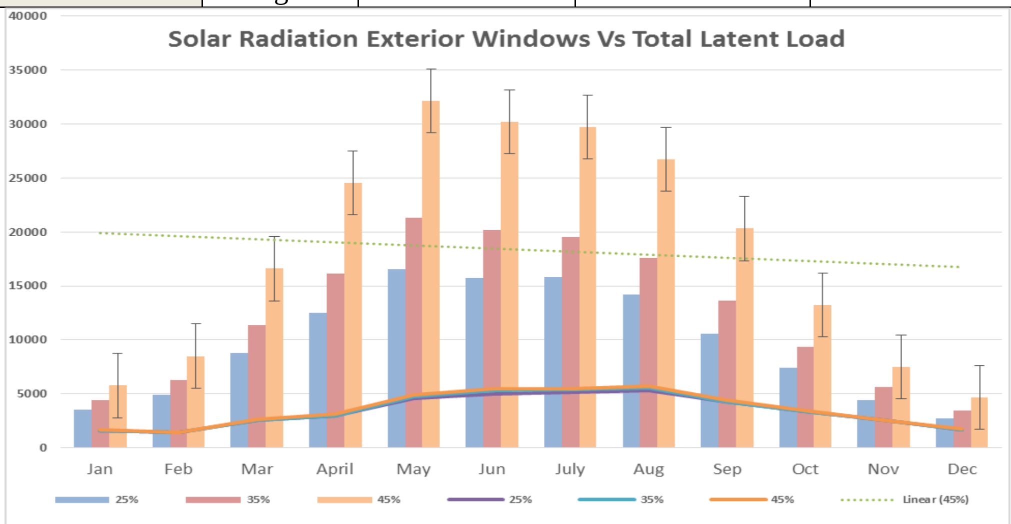


Figure 19: Relation of solar radiation exterior window and total latent load of the Improved case

7.5 Comparing the Rate of Total latent load inside the halls in the Base Case and improved cases

Figure (20) shows that, compared to the building's basic condition, total Latent loads reduced from 9919 kilowatt-hours to 2900 kilowatt-hours in March, a 70% improvement rate, and from 15250 to 5500 in August, a 65% improvement rate.

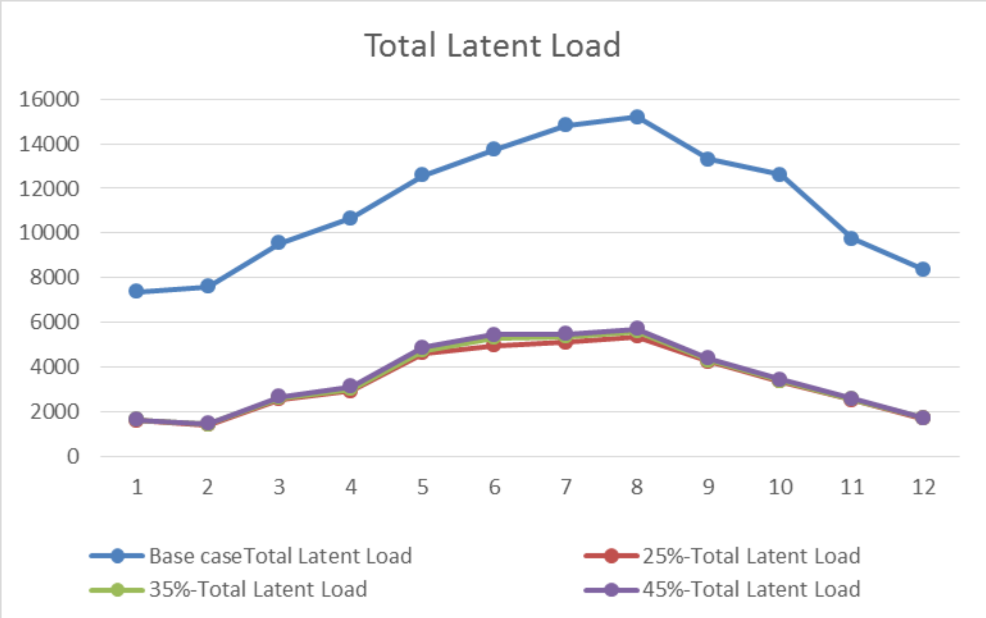


Figure 20: Relation of total latent load in base case and Improved case

8. CONCLUSION

The research paper was able to improve the thermal properties, daylighting, and energy consumption of indoor gyms by:

- By adjusting the percentage of window wall ratio (WWR%) and ceiling to 45%, the study paper was able to improve the thermal performance, daylighting, and energy consumption of inside sports halls:
- Glazing windows with a transparent phase change material (PCM Translucent).
- Installing a sky court system and a saw-toothed ceiling design to reduce glare and allow natural lighting to reach the halls' depths.
- Insulate walls and ceilings with paraffin phase change material (PCM paraffin RT28HC).

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