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Comprehensive Analysis of Combined Pile Raft Foundation using PLAXIS 3D, SAP 2000, and ELPLA

Nada Salih
Hicorner consultancy
hi.cornr@gmail.com

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ABSTRACT

This study thoroughly investigated the thermal characteristics of three distinct glazing types utilized in Dubai: double glazing (DGU), triple glazing (TGU), and quadruple glazing (QGU). A thermal chamber was constructed employing these three glazing forms, which underwent exposure to the severe summer conditions representative of Dubai. The thermal metrics within the chamber were documented and subsequently compared for analytical purposes. Environmental data loggers were placed inside to monitor air temperature and humidity in three compartments. The objective was to compare thermal performance in (QGU), (TGU), and (DGU) compartments due to U-value differences. The QGU compartment was expected to have a lower temperature, indicating better thermal performance. To establish a benchmark, an independent weather station was used to measure the microclimate at the experimental location, and south orientation was selected for the test. Findings show significant thermal efficiency differences between glazing types, as (QGU) performs exceptionally well, with lower air temperatures compared to (TGU) and (DGU). The findings were provided by the heat index formula and supported by the data that provided better thermal comfort indoors.

Keywords: *double glass unit (DGU), triple glass unit (TGU), quadruple glass unit (QGU), heat logger (HL), heat index (HI), delta T (ΔT or DT), delta RH (ΔRH, or DRH).*

1.The Narrative.

Glass has undeniably prevailed in Dubai, propelling the city into a promising future with unwavering confidence (Reisz, 2021). The narrative tells double glazing system has been standard in Dubai for a long time, while triple glazing is reserved for healthcare facilities. Concurrently, quadruple glazing is emerging in locales such as offices, airports, and public institutions. The quadruple principle is employed in advanced glazing systems, such as vacuum glass, which consists of multiple layers of glass separated by vacuous gaps (Qiu et al., 2025).

The question of interest concerns which approach is most beneficial for Dubai's extraordinarily hot and humid environment (Calautit et al., 2025)

This paper puts forward a simplistic hypothesis that the addition air gap enhances thermal efficiency, aligning with the long-standing notion that thicker is better.

This principle represents a fundamental antithesis to the notion of vacuum glass lining utilizing passive glass, which necessitates heightened scrutiny to enhance energy management in light of the impending constraints anticipated in future electrical power supplies (ALKodmany, 2020).

2.The Objectives

The research endeavors to substantiate the efficacy of specific glazing types in hot, humid climates and to find optimal glazing solutions tailored to the architectural landscape of Dubai. The objective is to investigate a range of glass types, with a distinct focus on multilayered glass.

The central aim of this experiment is to find effective glazing options by replicating an air gap within multilayered glass, which is expected to improve the U-value, Solar Heat Gain Coefficient (SHGC), and Shading Coefficient (SC). This study specifically explores the thermal performance linked to the expansion of the air gap in quadruple glazing, which is viewed as an evolution beyond double and triple glazing.

3.The Climate

Dubai's climate, situated within the Tropic of Cancer at 25.16°N and 55.18°E, is characterized by intense heat and humidity, recognized as a coastal city within Zone B0 as per the ASHRAE updated report in (2018, 2021) (Dubai Codes, 2021).

Dubai has an extremely hot desert climate, as illustrated in Figures 1.

It emphasizes that summer constitutes the longest season characterized by elevated temperatures and humidity, with daytime temperatures soaring to 50°C and humidity levels reaching up to 90%.

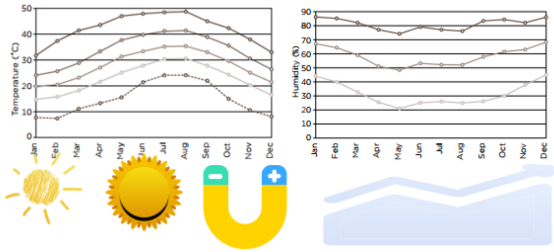

Figure 1 shows the air temperature & humidity of Dubai (Dubai Codes, 2021)

Figure 1 depicts the air temperature in a dome-like configuration, while the sun icons denote the intense heat that begins in May and endures until the conclusion of September. Conversely, the right side depicts the ascending trend in humidity, represented as an inverse dome, wherein the peak temperatures consistently coincide with the lowest humidity levels and vice versa.

4.Dubai Glass Building & Research Review

Dubai regulations aim to enhance energy efficiency in glass buildings and reduce carbon emissions. Double-glazed windows have been mandatory since the 1980s. New glass products are triple or quadruple-layered for better insulation in critical environments. Figure 3 showcases glass buildings in Dubai.

Figure 2 illustrates the glass buildings located in Dubai.

The A captivating leftward view of downtown, 2024, captured from a highway bridge designed for the Burj Khalifa. The middle picture in B depicts the Financial District, 2023. The last in C is the roof of the podium of the index building, 2010 .All pictures are by the author, 2024.

The decision-makers' opinions mentioned in the Dubai Map 2040 focused on processing the scientific accomplishments as much as possible without limitation. The ambition to create a Dubai digital twin is considered essential among architects and engineers. Shifting away from traditional trends is the new normal. In the Burj Khalifa, the world's tallest building, the architectural design is a marvel of modern engineering where various glazing types are used. Some sections have quad glazing, while others have double glazing or triple glazing. The glass in the Burj Khalifa is silver low-E with a solar heat gain coefficient (SHGC of 0.3), and a shading coefficient SC of 0.35. Figure 3 shows the Burj Khalifa.

Multi-layered glass, including Quad panes, is designated for office envelopes for extreme cold or intense heat. They are compatible with the newly implemented fresh air addition systems, which are commonly integrated into high-rise HVAC systems in Dubai. Advanced innovations in glass can be observed in the Emirates Towers (built in 2000) , recently in the low-rise MBRL Library building (2022), and in Al Maktoum International Airport (DWC , or OMDW), which partly opened in 2023 but is expected to be completed in 2050.The practice of retrofitting or renovating existing façades and structures is observed, despite the city's relatively recent establishment, leading to the emergence of a multi-layer glazing system as an enhancement.

The One Za'abeel twin towers and the Al Wasl twisted tower, both newly completed and well-situated in Dubai, incorporate quadruple and triple glazing where deemed essential, in addition to double glazing. The architectural design showcases a sleek, volumetric rectangular form, while the wind-deflecting components are crafted as vertical cut glass liner pieces, as mentioned in the developer's blueprints. Double-skin glazing was implemented on the upper floors of the structure to emphasize the concept that no single glazing solution is optimal. The building was engineered to withstand seismic and wind pressures, with glass and steel deliberately chosen for their durability and suitability for tall structures' skeletons. Figure. 4 left is One Zabeel & right is Al WASL by the author, 2025

Fig. 3 Burj Khalifa. Pictures by the author.

Fig. 4 left is One Zabeel & right is Al WASL by the author, 2025

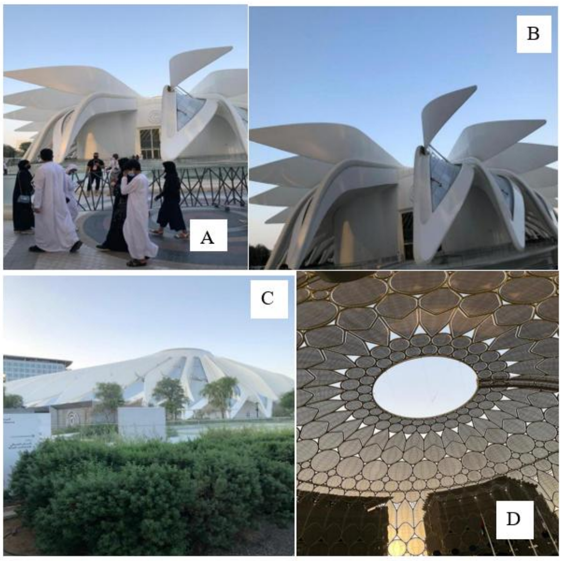

Figure. 5 showcases the Expo Wing of 2020, situated in the top left A,B,C alongside the Expo's transformative glass of the central dome as D,pictures by the author 2021.

Expo 2020 Dubai exemplifies the utilization of a passive combination of double, triple, and quad glazing as necessitated, as evidenced by government publications and actual site data. The central dome building's architectural design includes glass facades that change color, controlled by a shading system. The Emirates Wings at Expo 2020 in Figure 5 have glass envelopes and canopies designed to adapt to the sun's movements in different seasons.

The glass products utilized in Dubai adhere to European standards (EN 410) and U.S. standards (NFRC 300/200). Choosing triple or quadruple glazing is considered a progressive option over double glazing, which fails to meet the increasing energy requirements. The triple-glazed assemblies, characterized by an air gap or laminated construction, in conjunction with PVC framing as opposed to aluminum, are currently operational, as depicted in Figures 6 shows A: triple glass & PVC frame, B:triple glass, C:quadruple glass, and D:double glass.

The implementation of triple glazing in residential projects has been utilized by architects for several years. In contrast, quad glazing, as shown in Figure 6 C, is employed in offices, educational institutions, and healthcare facilities.

Fig. 6 shows a real sample of glazing types used in Dubai.

The left A illustrates triple glazing with a PVC frame. B depicts triple glazing with lamination. C showcases quadruple glazing with an air gap & outside protective heat mesh. D is double glazing with 21mm air gap and protective mesh. The pictures were taken by the author in 2024

Recent advancements in thin glass technology and lightweight frames have facilitated a reduction in the weight of triple or quad-glazed windows (as outlined in the NREL manual). The cost differential between triple and quadruple glazing, when weighed against the enhanced performance benefits, has rendered their reintroduction more viable (Kiatreungwattana et al., 2021).

Ultra-transparent glass is used in quadruple, triple, and double glazing systems to facilitate solutions for future zero-energy buildings (Bakker, 2020). The implementation of quadruple glazing options can enhance energy efficiency, as it facilitates the integration of solar-collective thin-film technology, as mentioned by (Bonham, 2020).

The THERM 7/WINDOW 7 NFRC simulation manual (July 2024) stated that triple and quad glazing have engineering complexities, including determining insulation placement and applying alternative coatings or films. Additionally, besides the cost, managing advanced manufacturing techniques and transportation challenges is also present (Delgado ,2021).

The integrated phase-change materials (PCM) situated between two panes of glass (Sadooghi et al., 2021) necessitate an inquiry into four-pane glazing systems. These configurations can yield a substantial reduction in heat gain.

The incorporation of gas infill renders them potentially as robust as solid walls. However, the challenge lies in the fact that humidity undermines the efficacy of air insulation, as it diminishes the insulating capacity when moisture is absorbed. These quadruple passive windows exhibit a 50% enhancement in thermal efficiency compared to their counterparts (Kralj ,2022, 2023).

5. Glass Variables

Quadruple glazing and triple glazing exhibit lower U-values in comparison to insulation or brick (Ragab, 2023) . A single glass pane exhibits a U-value of 5.4 W/m² K, and the air thermal conductivity is 0.025 W/m² K, while a local double-glazed window has a thermal transmittance of 2.1-2.5W/m² K.

Insulating gases such as argon (0.017 W/m² K), krypton (0.0094 W/m² K), and xenon (0.0056 W/m² K) significantly enhance thermal performance; however, their usage remains infrequent. Additionally, window frames are progressively evolving to become more minimalist or entirely concealed.

The width of the air gap typically ranges from 12 mm to 20 mm. Researchers recommend that the air gap be between 15 mm and 16 mm for maximum thermal efficiency (Durakovic, et al., 2020).

Such gaps are clear in the new towers but depend on the properties of the gas insert or the number of layers used, as a few researchers indicate that the optimal gap is 14-15 mm for argon, 9-10 mm for krypton, and approximately 6-7 mm for xenon. Table 1 illustrates the optimal gap size for the different insulating gases.

Table 1 shows the optimal gas and gap sizes, Duakouvic (2020).

Air	12 mm -20mm as the best gap is 16mm
Argon	14-15 mm as the best gap is 12 mm
Krypton	9-10mm the best gap is 8mm
Xenon	6-7mm the best gap is 5mm

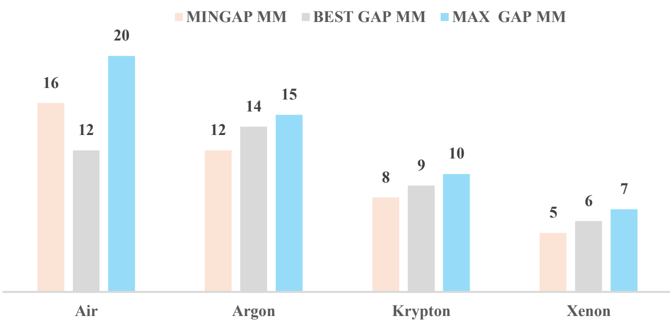

Figure 7 shows Gas & Gap relation BETWEEN GLASS PANS

The majority of local manufacturers utilize a 12 mm air gap, which is also the case with the glass enclosure in this paper experiment. Figure 7 shows the gap relation.

Multi-layered passive glazing uses air that is freely available and does not require special handling, like gas refills, making it a sustainable choice for this experiment. In locally double-glazed units, the outer pane is low-E, with a minimum thickness of

6 mm or more than the 12 mm air gap, followed by 6 mm of clear glass.

In triple-glazed units, the gap is widened to approximately 19 mm to 20 mm to accommodate the frame. In this experiment, all glass samples had similar air gaps to replicate the standard local window configuration. In this research, the primary layer featured a low-emissivity (low-E) glass panel, while the subsequent layers were constructed of clear, standard glass for local fabrication. No insulating gas was employed; only regular air was used.

The air gaps were all standardized at 12 mm in accordance with the typical low-E glass window specifications (Mann et al. 2023) .Table 2 illustrates that the low-emissivity (low-E) glass enhances the U-value to a certain degree, as the (R)resistance is increasing. The table shows that using low-E is quietly employed to avoid glare outdoors while controlling the VLT indoor lighting level. It reduces total heat flux by up to 34% and enhances heat transfer resistance values from 0.50 m².K/W (without coating) to 0.632 m².K/W (with coating).(Koshlak et al., 2025) & (Flavonoid et al., 2022).

Table 2 shows low-emissivity (low-E)		
Quadruple glass (6-8mm)+ air (A)12mm	Low-E scenario	R-value calculated = 1/U
6-A-6-A-6-A-6	No low-E	2.532
6-A-6-A-6-A-6	One low-E	3.157
6-A-6-A-6-A-6	Two low-E	3.8782

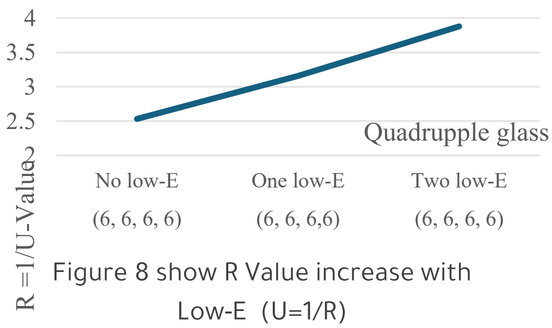

Figure 8 show R Value increase with Low-E (U=1/R)

The frame plays a role in maximizing the energy efficiency of the glass, leading to an overall enhancement of approximately 30-40% , like timber or a new, advanced type.

Additionally, the integration of smart window technologies, which allow for dynamic control of light transmission, offers users the ability to enhance comfort and reduce reliance on artificial lighting and heating, thus contributing to overall energy savings (Johnson, 2023).

A frame was omitted in the experiment, with a standard spacer being utilized, and all glass panels shared the same 6 mm thickness. The panels with spacers were attached together during the factory assembly process.

Many architects prefer a concealed frame style or the so-called minimal style that is hidden either by glass or by other building features. Selecting UPVC or timber materials assures high-quality installations, even though they require additional expenditures (Favoino et al., 2022).

Table 4 illustrates glass variables; factors are evaluated in Dubai in accordance with local regulatory codes rather than solely relying on laboratory or manufacturer certifications, as mentioned in Table 4

Table 4 illustrates glass variables.				
Glass type	U-Value	SHGC	SC	VLT (%)
Single glass	5.7	The hue and clarity of the glass.		
Double	~1.6 - 1.8	~0.50 - 0.55	~0.58 - 0.64	~70 - 75
Triple glazing	~1.0 - 1.2	~0.35 - 0.40	~0.41 - 0.46	~60 - 65
Quadruple glazing	~0.6 - 0.8	~0.25 - 0.30	~0.29 - 0.35	~50 - 55
UPVC or timber frames improve the U-value by 30-50% .				

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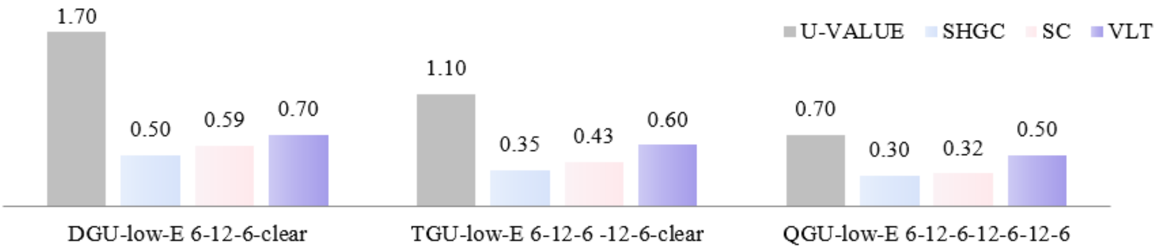


Figure 9 shows U-VALUE + SHGC+ SC +VLT

Cutting-edge systems incorporating rare metal additives to the glass or frames, and creating thermal bridging, or using polymers for superior heat rejection, claim to achieve remarkably low U-values as low as 0.8 W/m² K (Aksamija ,2021) .

The shading coefficient (SC) in climates such as Dubai varies to values ≤ 0.4 to minimize cooling loads; lower values are considered optimal due to the absence of any shading elements besides the glass envelope in towers and this paper's experiment.

The data presented were obtained from the European standards EN410/673, utilizing WinDat WIS version 3.0.1 software, LBNL Window 7.3/7.4 software, and various calculators such as Therm and EnergyPlus.

The U-value illustrated in Figure 9 presents the concept in a more simplified manner, highlighting that the inclusion of frames undermines the quality of the U-value, rendering it inferior.

4. METHODOLOGY

The methodology involves employing known glazing types of facades to define which glass type provides the better indoor configuration or is optimal based on the specific glass type and its orientation.

The potential of utilizing multiple glass layers remains underexplored (Sadooghi, 2021) & (Schittch, 1999), therefore, the research uses the scientific method and follows a systematic bottom-up framework of available applications.

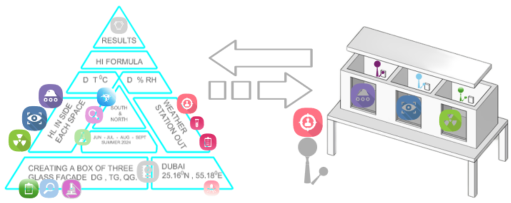


Figure 10 illustrates the methodology.

Data gathered during the summer of 2024 will be rearranged based on the heat index, utilizing temperature and relative humidity to derive the outcomes.

Figure 10 illustrates the straightforward methodology of the box construction, featuring three glass facades that embody a minimalist glazing aesthetic. This structure is situated in a monitored location in Dubai. Heat loggers (HL), denoted as colored dots representing the glass type color, are positioned within the interior, alongside one red external (HL) functioning as a weather station, hereafter referred to as (ENV) .

Each facade window showcases a distinct type of glass: green represents Double Glazed Units (DGU) , blue signifies Triple Glazed Units (TGU), and purple is assigned to Quadruple Glazed Units (QGU) .The same names are given to the heat logger inside each compartment.

The experiment incorporates three distinct compartments, each featuring various glass façades typically used in Dubai.

Simultaneously, a heat logger is thoughtfully installed at the center of the chamber, documenting the indoor thermal gain. In alignment with the findings of (Zukowski ,2025), the results are expected to shed light on enhanced thermal performance outcomes.

The bottom-up paradigm relies on authentic data gathered from the field, in accordance with the established NFRC 201 protocol known as the hot box. The study also follows (Santamaria, 2020) as she used water instead of air in a box to test indoor comfort with different fluids compared to air.

Additionally, the experiment is hinting to (Chmurny, 2016) (Qiu et al., 2025) who drew the evaluation of triple and quadruple glazing, referring to the design engineering of the insulation position between the glass layers or, as he mentioned, the coating position.

4.1 The Glass Box

The experimental setup entails the construction of a chamber that measures 170 cm in length, with an inside height and depth of 50 cm each. This chamber is segmented into three compartments, each measuring 50 cm in inside width, ensuring uniformity in size. A 170x60x60 cm glass box was divided into three 50x50x50 cm sections. Each section housed one double-glazed unit (DGU), one triple-glazed unit (TGU) , and one quad-glazed unit (QGU) with a facade of 30x40 cm glass panels, as advised by test labs.

Internal heat loggers were positioned inside each compartment facing the glass. Another heat logger, serving as a weather station, was placed outside. The box faced south from June to September 16, 2024, then north until September 30. Figure 11 shows the glass enclosure.

The walls and ceiling of the chamber are fabricated from styrofoam 5cm thick, a material commonly employed for roof insulation in buildings. All components are assembled using fast-acting adhesive glue. The glass units were skillfully assembled as a singular entity, free of frames, precisely tailored to the dimensions of 30 cm x 40 cm, similar to those found in laboratory analyses. The glass units were affixed to the chamber facade utilizing foam and securely sealed with plastic tape. Figure 11 shows the complete mockup with information.

The experiment was conducted in Dubai, with the southern orientation purposefully selected. Figure 11 illustrates the specifications of the glass box, which contains a heat logger, and another is located outside, approximately 1.50 meters away from the chamber, where the heat logger is named ENV, as the weather station marked in red. Each glass unit was sealed without any provisions for ventilation, as in a new high-rise building (Kralj, 2023) &(Calautit et al., 2025).

The glass box was elevated to a height of 1.50 meters, where 174 Testo heat loggers (HL) were installed at the center to facilitate data collection. Furthermore, a separate heat logger, identifiable by its red hue, was placed outside, roughly 1.50 meters from the glass box to monitor local climatic conditions. Figure 12, providing information about the glass of this hot box at the site, was fixed to a table. All panes are positioned using setting blocks and secured with silicone or plastic. Frames are rendered unnecessary, as clearly illustrated in Figure 12 that shows material specifications. The outermost pane is made from low-emissivity tinted reflective glass, akin to the local glass used in buildings, while the subsequent layers are composed of clear glass. The air gaps measure 12mm, and the glass is 6mm, as fabricated locally. Figure 12 shows glass details, and Figure 13 shows the real glass box fixed at the location. Figure 12

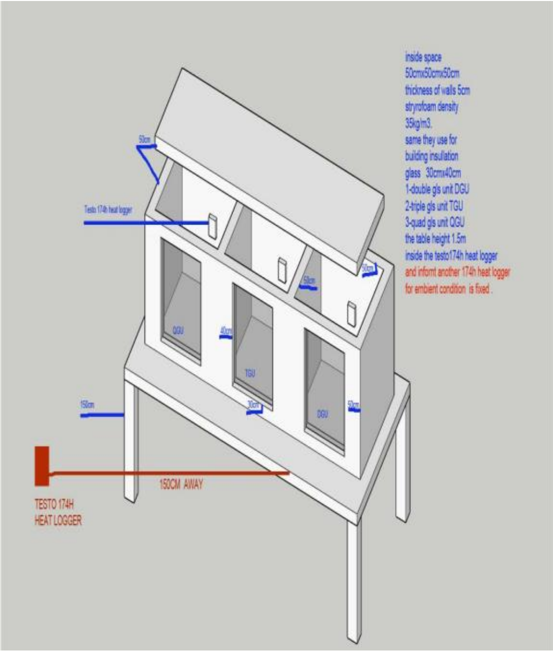


Figure. 11 depicts a glass enclosure & material specification.

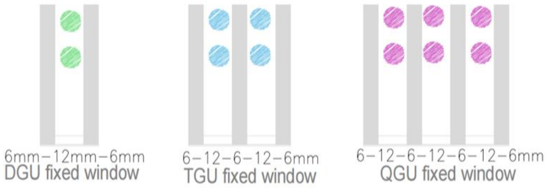
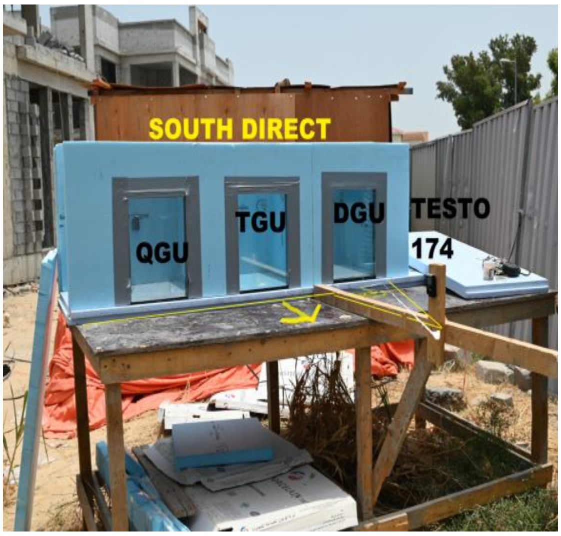


Fig. 12 shows the combination of the three glass types.



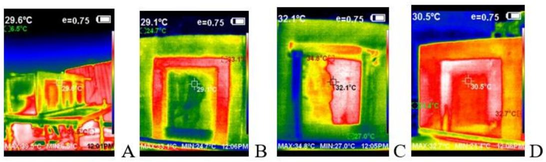


Figure. 13 The glass hot box at the site was fixed to a table.

Thermal images A is a full box, B is QGU,C is TGU, D is DGU as DGUmost heated.

The entire assembly was affixed to a wooden table measuring of 90cm, as available at the location near to ordinary construction site with usual activities without shade.

Throughout the duration, there was a deliberate absence of ventilation, maintaining a fully enclosed environment, as clearly shown in Figure 13 closed without ventilation like a hot oven, as thermal images show.

The construction methodologies were aligned with the Passive House standard for energy-efficient design, initiated by Dr. Wolfgang Feist in Darmstadt, 2005, Germany, providing a guideline that is frequently assimilated into Dubai's building regulations. It is shown in Figure 14 that the three units of glass are fixed to the heat chamber box as drawn in detail. All materials employed in construction serve distinct purposes, such as the polystyrene utilized for roof insulation and the rapid-setting adhesive applied for sealing pipe coring sleeves and openings, while glass is commonly used for windows.

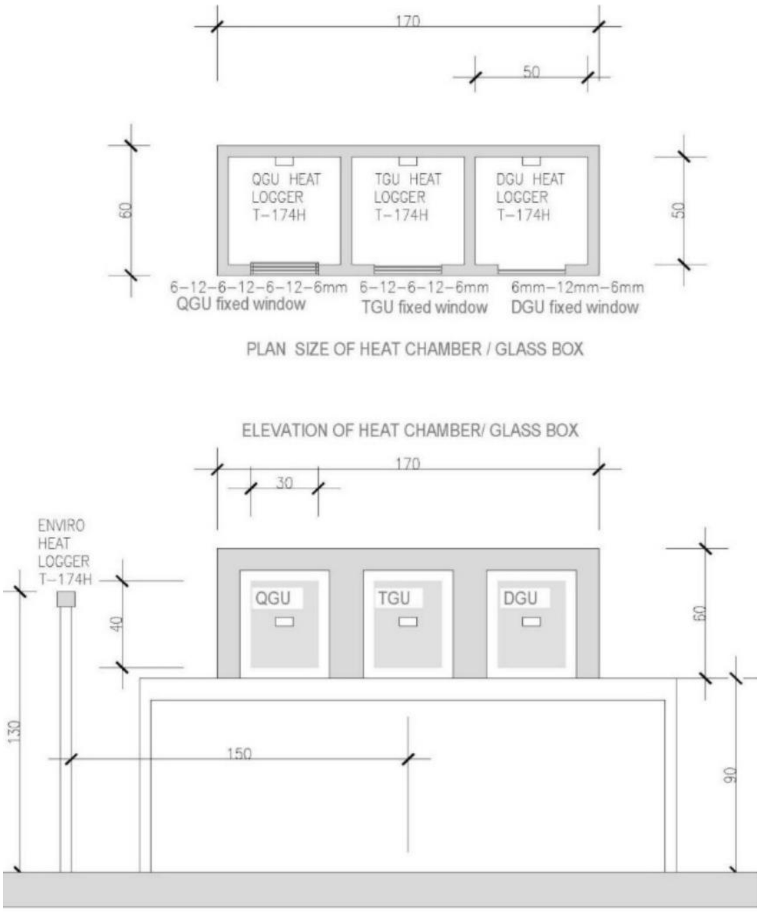


Figure. 14 The glass box shows the CAD detailed drawing for size and height.

4.2.The Heat Logger (HL)

The heat logger (HL) is the same one used in labs to control the temperature, featuring an advanced interface and continuously recording data on an hourly basis, with the information subsequently extracted through specialized software for digital record-keeping. Figure 15 shows data extraction from (HL) through the interface and related software, with each (HL) corresponding to the glass units facing them being labeled as a glass type. Heat loggers were calibrated to collect data on an hourly basis from the commencement date of June 19th 2024 to the conclusion of the experiment conducted on September 30th.

The data was then sorted by the heat index formula and other equations to clarify the findings.

Figure 15 illustrates (HL) data extraction process to CSV file.

4.3. The Glass Units

The glass units were crafted from 6 mm commercial-grade material available in the local market, as specified in Table 5, which displays all variables following the authority's quality control as per DM Code 2021 that governs the manufacturer's certification as an advanced attempt to manage higher fabrication quality in the UAE.

Table 5 shows glass specifications.		
The outer glass layer is of low-E type.		The inner glass layer is clear.
The outer layer follows EN410 & US NFRC		Second, third, & fourth panes.
The Hue-coat	Blue-green AS14T	Clear glass, DSRI.
Light external reflection:	20% outer layer	36% inner pane
Light internal reflection:	30%	22%
EN410 SHGC /G value 12mm air:	0.11	0.19
EN410 SC:	0.13	0.22
U-value	1.84W/m2. K	1.65W/m2. K
US NFRC SHGC:	0.12	0.18
NFRC SC:	0.11	0.15
The U-value is provided:	1.84W/m2. K	1.7 W/m2. K
The U-value estimate is provided:	1.84W/m2. K	1.66 W/m2. K

The U-value in Table 6 shows the glass variable in the box, which worsens during the summer months as materials reach their saturation point for absorbing more heat. This principle applies to air and glass, including the frame (Musgraves et al. 2019). The specified U-value pertains to the glass and the frame together. It is worth noting that the metal frame adds an extra 30-40% to the glass U-value Memari (2013).

Table 6 presents the glass box U-value according to the DM Codes 2021.				
	DGU	TGU	QGU	Horizantal
Summer U-value W/m2.K	2.1-3.0	1.8-2.2	1.3-1.7	1.3-1.7
No frame U-value	1.6-1.8	1.1-1.2	0.6-0.8	
SC as EN410	0.5-0.6	0.4-0.46	0.29-0.35	0.25-0.2
SHGC as EN410	0.50-0.55	0.3-0.4	0.25-0.3	0.21-0.17
VLT -Visible light transmitted	0.7-0.8	0.6-0.75	0.5-0.65	0.5-0.65

4.4.The Heat Index

The heat index equation was used to derive a numerical value by incorporating both temperature and humidity. As the distinctions among the various types became apparent through the huge data collection, the heat index method was necessary to validate the findings that relate both temperature & humidity variables in one result.

$$HI=C_1+C_2*T+C_3*RH+C_4*T*RH+C_6*RH^2+C_7*T^2*RH+C_8*T*RH^2+C_9*T^2*RH^2$$

The heat index equation was used to forecast the combined impact of temperature and humidity, both of which govern indoor air quality, which is crucial for comfort and overall satisfaction. It is important for the health, comfort, well-being, and productivity of building occupants to achieve optimal levels of PMV or PPD indoors without conducting any surveys. The ideal temperature range is set at 20-24°C for summer and 23-27°C for winter, while maintaining humidity levels between 30-60% to prevent excess moisture or dryness. All data points were recorded for temperature and an equal number for humidity, all calculated using CSV files of all types (ENV, DGU, TGU, QGU) and saved on GitHub.

5.The Results

Research indicates that evaluating indoor temperatures against the surrounding environment is essential, regardless of orientation. The glass box was placed facing south, which is considered poor window positioning in the summer. Dubai Minicipality standards gave a ratio ideally kept at a maximum, set at 40% for all orientations. The north orientation is allowed to be fully open at 100% . Both the eastern and western sides adhere to U.S. regulations, maintaining an opening ratio of 40-50%. However, it is evident that a reevaluation of these ratios is imperative. In practice, these two orientations, having a low sun angle, are both avoided in design.

The research glass box without ventilation and was totally locked. The glass box container was never opened, even for inspection. It was securely locked in place, facing the southern orientation until mid-September.

The dataset encompasses the period from June 19 to the end of September 2024, comprising 2,377 hourly measurements. The findings reveal that QGU afforded the highest degree of thermal comfort, accompanied with stability, characterized by minimal variability in temperature differential (ΔT).

It exhibited a maximum internal temperature that was 8°C lower than the double-glazed unit and 6°C lower than the triple-glazed unit during daylight hours. This was provided at the end when loggers were out by the machine program itself without any interference.

Throughout the night, all units demonstrated comparable temperatures due to the elevated humidity levels, which were uniformly high across all units, although lower than the external humidity.

The average temperature differential (ΔT) between indoor and outdoor environments is as follows: QGU ≈ +0.76°C, TGU ≈ +0.93°C, and DGU ≈ +1.59°C. In terms of stability, QGU registers near TGU because the positioning of TGU is in a central location, safeguarded by two air gaps formed by DGU and QGU, as illustrated in Figure 14. However, QGU still has higher performance.

Table 7 presents the comprehensive results, indicating elevated temperatures attributable to intense solar exposure, as well as the model size in relation to its geographical location, orientation, and (HL) position.

The recalibration of the (HL) to be affixed directly to the glass, both internally and externally, was rendered unfeasible due to constraints imposed by the experimental size & timeline.

These findings serve as initial biases concerning U-value, rather than SHGC or SC, which frequently necessitate multiple trials, as numerous researchers have articulated.

Table 7 presents the period from June to the end of September 2024

Results	DGU	TGU	QGU
Mean ΔT (°C)	1.6	0.9	0.7
ΔT Std Dev (°C)	3.9	3.6	3.4
Mean Indoor Temp (°C)	39.7	39.2	38.9
Mean RH (%)	48.3	48.5	48.6
Mean ΔRH (%)	-2.6	-2.2	-1.8

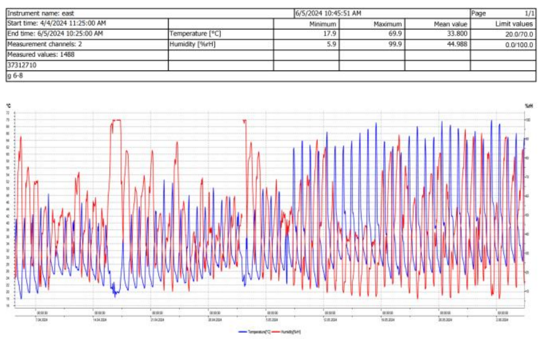


Figure 16 HL supports complicated graph information difficult to comprehend.

The HL is providing graphs for information, but unfortunately, they are not clear, as shown in Figure 16. The graph looks general and not useful; therefore, most figures are based on calculated data from CSV provided by HL.

In comparing a week's worth of data from the glass box oriented southward to that of another week facing north, with the objective of evaluating indoor thermal and humidity performance, the QGU distinctly emerges as superior to the other data obtained from (HL) for TGU & DGU.

The provided Table 8 details the values of a week at the north compared to a week at the south, reflecting mid and the end of summer as the orientation transitions. It is apparent that the zenith is achievable at mid-summer and the QGU is most closely aligned with ENV, where the delta T (ΔT / DT) is less than that of all other measures, giving the highest performance, as shown in Figure 17 and Figure 18.

Table 8 comparing QGU , TGU , DGU at South and North

Metric	DGU-south	DGU-north	TGU-south	TGU-north	QGU-south	QGU-north
ΔT mean VALUE	2.4	0.04	2.08	-1.32	1.8	-0.3
ΔT STD	3.6	3.5	3.3	3.64	2.9	3.2
T MEAN	41.9	36.9	41.8	36.8	41.2	35.1
T MIN	31.6	23	31.2	22.9	31.2	21.8
T MAX	61.7	60.1	60	56.1	59.9	58.9
Δ RH MEAN %	-5.9	10.6	-5.7	11.4	-5.01	12.1
Δ RH STD	6.2	20.6	5.7	17.9	4.9	20.1
RH MEAN	49.4	59.4	49.6	59.1	50.1	58.7
RH MIN	12.6	10.9	13.5	13.8	14.1	10.5
RH MAX	82	99.1	82	96.2	81.2	98.7

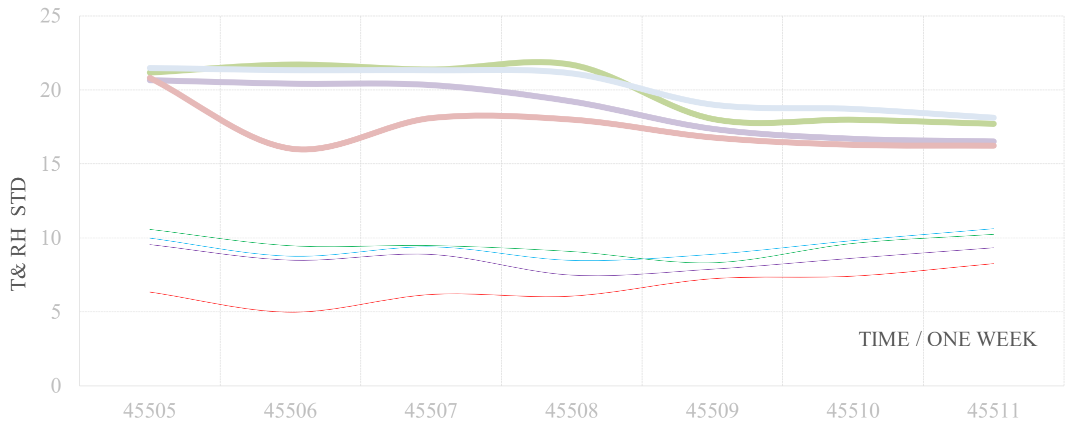


Figure 17 Daily SUMMARY one week south

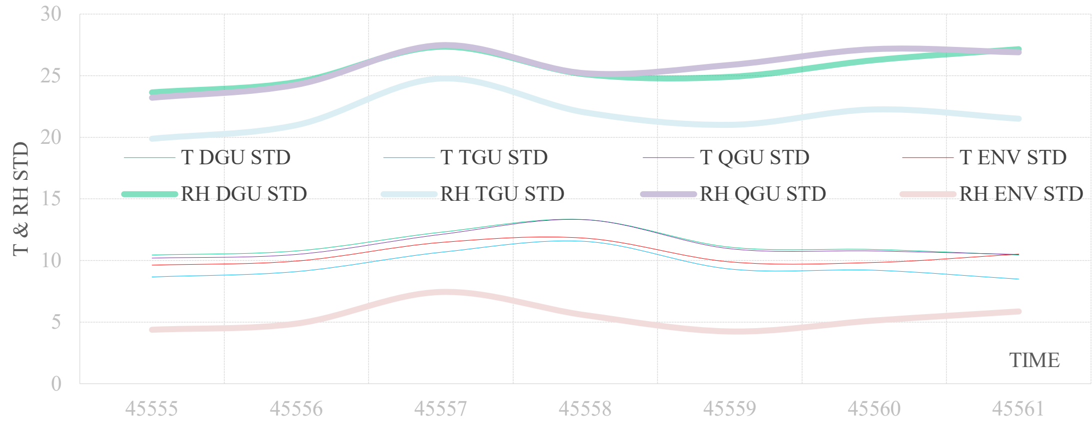


Figure 18 Daily SUMMARY one week north

5.1.Temperature & Humidity

The main point is that all glazing demonstrates a higher temperature relative to the outer HL, so-called (ENV) .The mean temperature elevation for Double Glazed Units (DGU) is over +2.9°C during the period from 10 AM to 3 PM, while the Triple Glazed Units (TGU) indicate a growth of roughly +2.1°C, with the Quadruple Glazed Units (QGU) revealing the least pronounced increase at +1.8°C. During nighttime hours, they all provide enhanced insulation characteristics.

Figure19 shows the delta T for QUG, TGU, & DGU . Additionally, Figure 20 shows the delta relative humidity for the same facing south. Both figures indicate better daytime positive efficiency for QGU compared to the others, then overlapping together at nighttime as negative.

Figures 21 and 22 pertain to the northern orientation as summer approaches its conclusion, where the QGU, TGU, and DGU seams underpin the Solar Heat Gain Coefficient (SHGC) rather than the U-value, owing to the sun's latitude and trajectory that facilitate shading or simply because they are distanced from direct sunlight. All thermal gain is derived from the surrounding reflection or refraction.

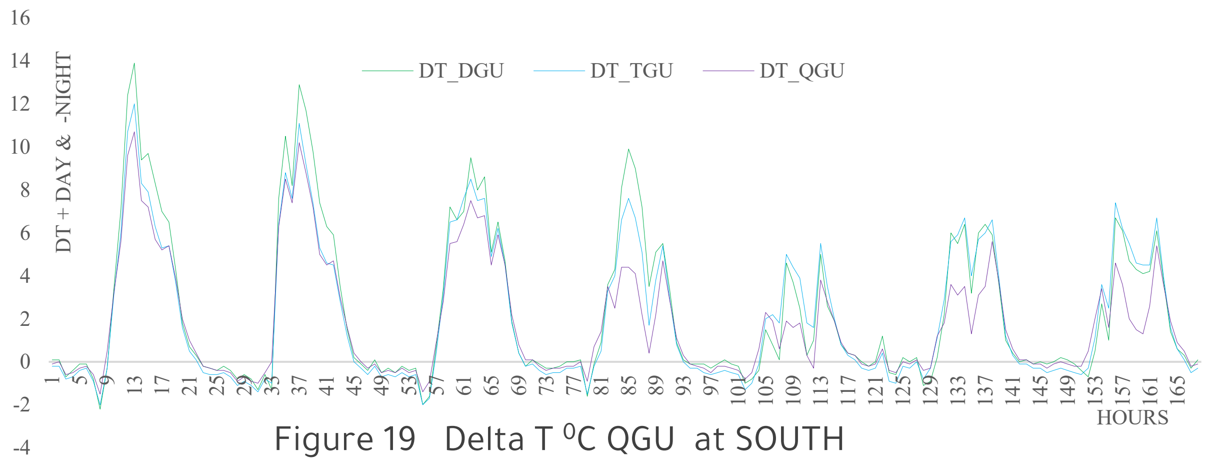


Figure 19 Delta T ^{0}C QGU at SOUTH

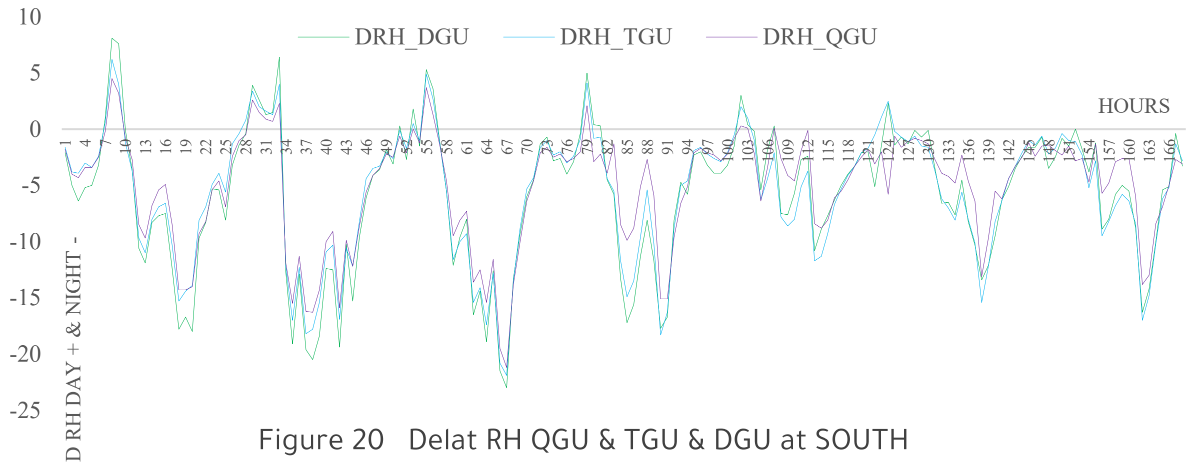


Figure 20 Delat RH QGU & TGU & DGU at SOUTH

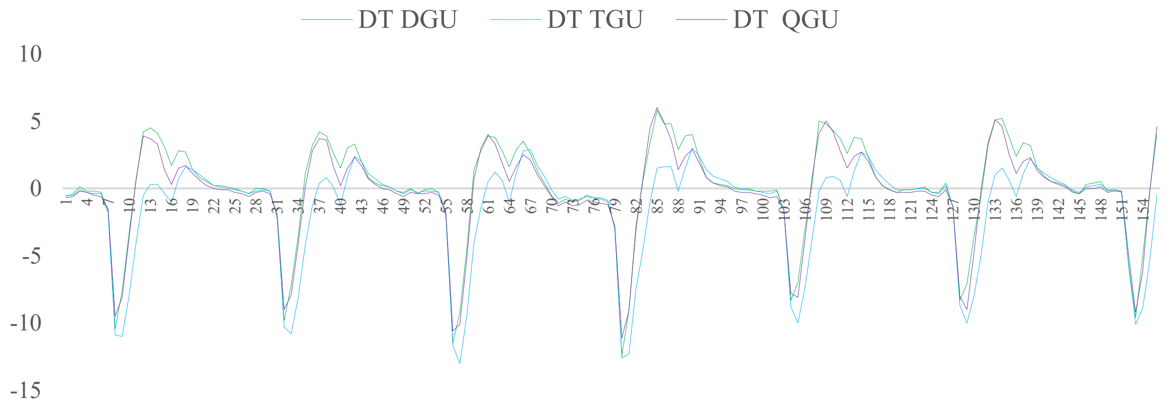


Figure 21 QGU DT FACING NORTH

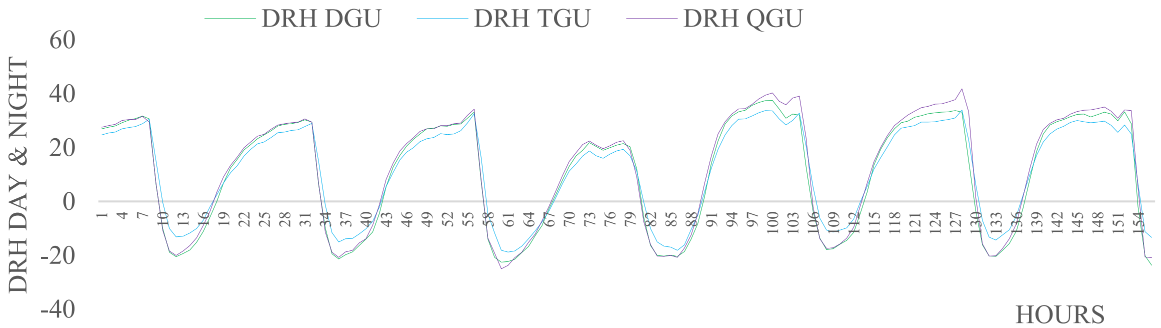


Figure 22 DRH QGU FACING NORTH

Temperature attains a mean value of 41 °C indoors for QGU in proximity to ENV, with recorded data indicating 40 °C. In contrast, TGU registers 43 °C, while DGU records the highest temperature at 44 °C. The data further reveals that the maximum temperature for QGU reaches 59 °C, compared to 55 °C for ENV; similarly, TGU and DGU exhibit temperatures of 57 °C and 62 °C, respectively. The minimum temperatures occur during the night, where all categories display values ranging from 0.1 °C to 0.2 °C for QGU and TGU, while DGU records a slightly higher minimum of 0.3 °C in comparison to ENV.

The data indicated that QGU possesses advantages with its smoothest temperature profile, exhibiting less extreme peaks and a more gradual temperature transition. TGU demonstrated balanced performance with moderate temperature increases. Conversely, DGU exhibited the highest temperature gain during daylight hours, characterized by maximum solar absorption and notable fluctuations. Furthermore, both QGU and TGU ensured consistent humidity levels, a characteristic also shared by DGU.

5.2 Diurnal Analysis

During the daytime (6 AM - 6 PM), it is recognized that all types of glazing exhibit a greenhouse effect, with the most pronounced temperature elevation occurring between 10 AM and 2 PM, characterized by reduced humidity levels.

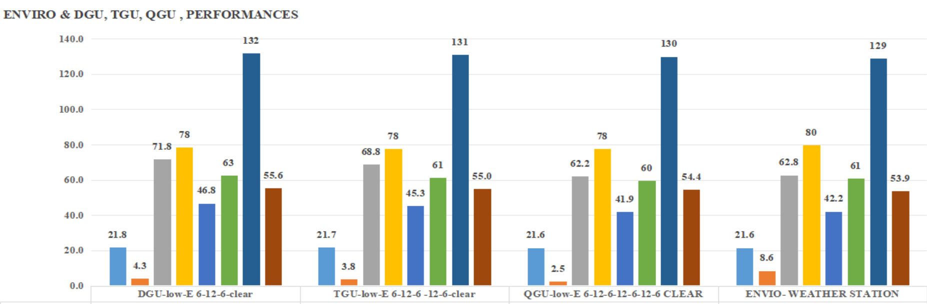
Conversely, in the nighttime hours (6 PM - 6 AM), all glazing varieties demonstrate slight insulation properties due to humidity.

The Lag Effect extends for an additional 1 to 2 hours beyond the external temperature variations, with QGU showcasing superior thermal regulation, thereby enhancing energy efficiency while mitigating temperature fluctuations.

The QGU exemplifies an optimal glazing selection, as it aligns seamlessly with the climate control objectives of Dubai, elucidating the clear trade-offs between maximizing solar gain and ensuring temperature stability.

5.3The heat index Results

The period under consideration encompasses the summer; however, for illustrative purposes, the designated timeframe is one week, during which the glass box is oriented toward the south and north. The heat index uses Fahrenheit, not Celsius; therefore, all temperatures were converted to ^{0}F then inserted into the formula. The results showed discrepancies in the heat index, exhibiting limited relevance attributable to the dimensions of the prototype, which are constrained. The accuracy of the instrumentation, coupled with the duration of the study, compromises the range among the various glazing types. The outcomes increase by about 17% as the experiment's components are a function of time and accuracy of the tools, which indicates that a modification factor is required.



	DGU-low-E 6-12-6-clear	TGU-low-E 6-12-6 -12-6-clear	QGU-low-E 6-12-6-12-6-12-6 CLEAR	ENVIO- WEATHER STATION
MIN T °C	21.8	21.7	21.6	21.6
MIN RH%	4.3	3.8	2.5	8.6
MAX T °C	71.8	68.8	62.2	62.8
MAX RH%	78	78	78	80
MEAN T °C	46.8	45.3	41.9	42.2
MEAN RH%	63	61	60	61
Heat index T F	132	131	130	129
Heat index T °C	55.6	55.0	54.4	53.9

Figure. 23 presents the outcomes of the computation of temperature and humidity.

The experiment demonstrated that during the daytime, the peak midday temperature reached a differential of 9°C, with the quad registering a maximum of 62°C, significantly better than the double scouring at 71°C, while the triple recorded a temperature of 68°C. Conversely, at night, all types narrowed to a mere 0.1°C, attributable to the influence of humidity, as shown in Figure 23.

However, converting these result values to Celsius in the final row of the figure reveals a range between 2°C and 4°C.The outcome was satisfactory, but it showed that an extended timeframe of approximately one year was needed, as suggested by researchers from Spain (Santamaria, 2020). The columns in Figure 23 illustrates that the quadruple measurement value closely aligns with the outdoor environmental temperature recorded by the heat logger, ranging between 1°C - 2 °C, as collected at the time. Figure 24 illustrates the translation of the heat index results for one week as a graph. The glass box prominently showcased the quad glazing (QGU) as superior to all alternatives, despite the absence of ventilation, any internal air circulation, or a cooling system. That explains why the quad QGU or multi-layered glazing became common practice in commercial buildings in Dubai as the accelerating climate heat wave became the new normal. The figures 24, 25 , 26 show the heat index results for the outside heat logger called Env in red compared to QGU in purple, TGU in blue, and DGU in green, with a clear gap between them. These figures provided one week for the heat index results, then down to three days, and then back to one day as QGU is nearest to ENV .

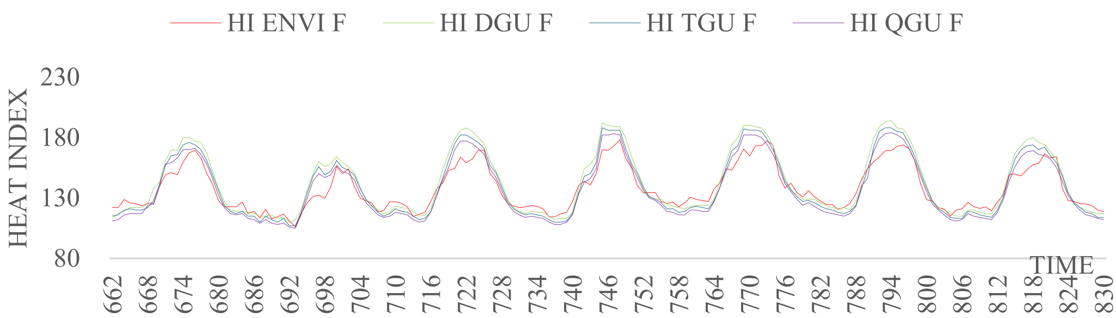


Figure 24 one week HI results at south

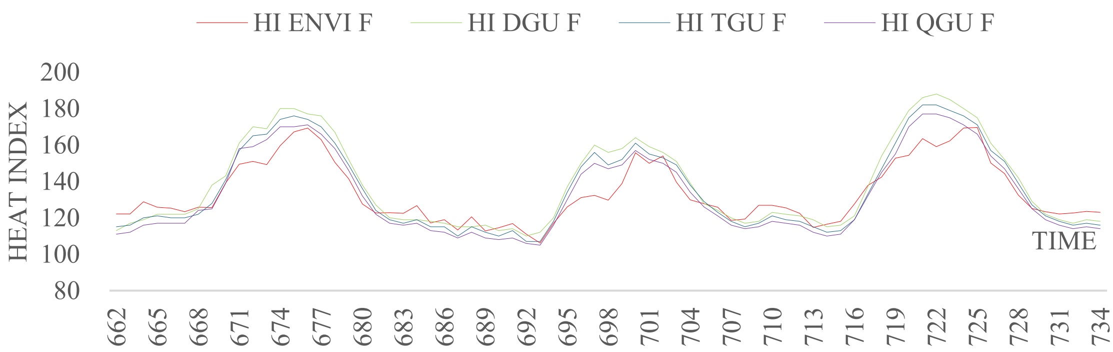


Figure 25 Three Days HI results at south

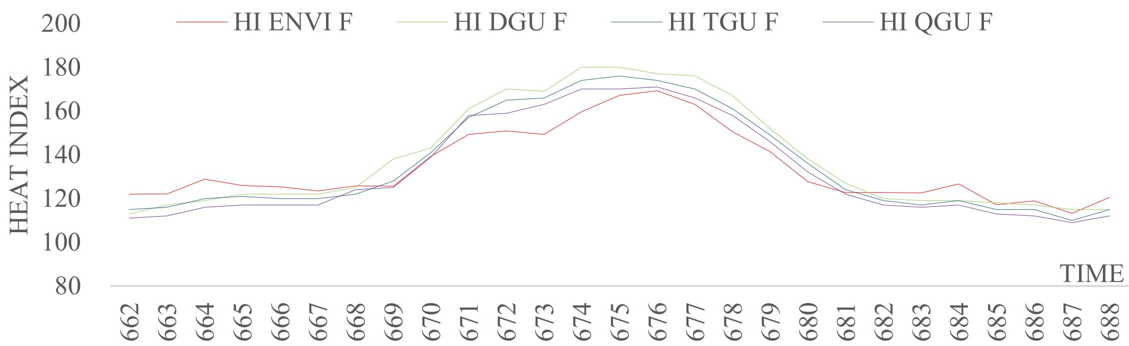


Figure 26 one Day HI results at south

Examining the one-day performances, the DGU exhibits a rather disappointing spike in comparison to the QGU and TGU.The results show clearer findings from three days and nights. It is reasonable to suggest that the QGU & TGU were similar in some dynamics, reflecting parallel distinctions during daylight hours.

Prolonged research could yield additional evidence by considering various factors, such as different orientations. Furthermore, the incorporation of higher-quality glass or the addition of an insulation layer might provide a more comprehensive understanding.

The superiority of QGU has resulted in an outstanding outcome, indicating that U-value serves as fundamental scientific guidance. That U-value demonstrates a marked advantage for QGU glazing in comparison to both triple and double glazing. The incorporation of an additional air gap within the QGU framework enhances its overall performance. Furthermore, there exists a pressing need for further investigation into the Solar Heat Gain Coefficient (SHGC) and Shading Coefficient (SC) to support these findings through additional trials.

The relationship of heat, temperature, and relative humidity is contradicting each other, as shown in Figure 27, making all the units remain within the same level when their temperature peaks during the daytime to 160 F, then reverses down at night below 120 F, while humidity is the opposite. Similar to the butterfly effect, it explains that all perform better at night.

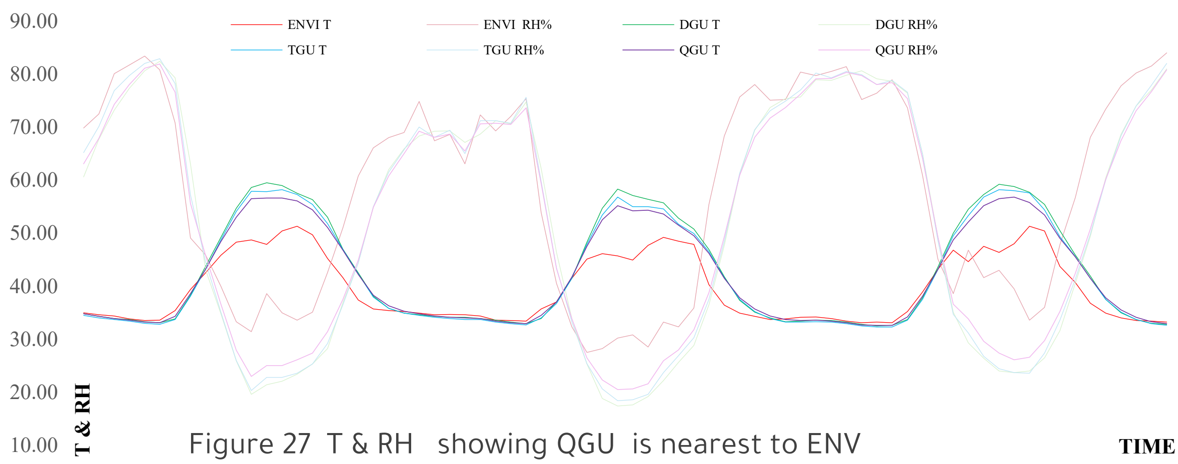


Figure 27 T & RH showing QGU is nearest to ENV it present the conflict of both as butterfly effect

The study of the glass box's performance was constrained to a two-week period when it was oriented towards the north. It revealed that the northern exposure remained in shadow due to the sun's elevated position during the summer months. Nevertheless, all types were largely comparable, as the duration of exposure in the northern orientation yielded fewer results compared to the southern orientation.

The results shown in Figure 28, 29, 30 ,the glass types exhibited comparable indoor performance values in the northern orientation, and all were situated in close proximity to one another. Notably, the quadruple glazing still demonstrated superior performance.

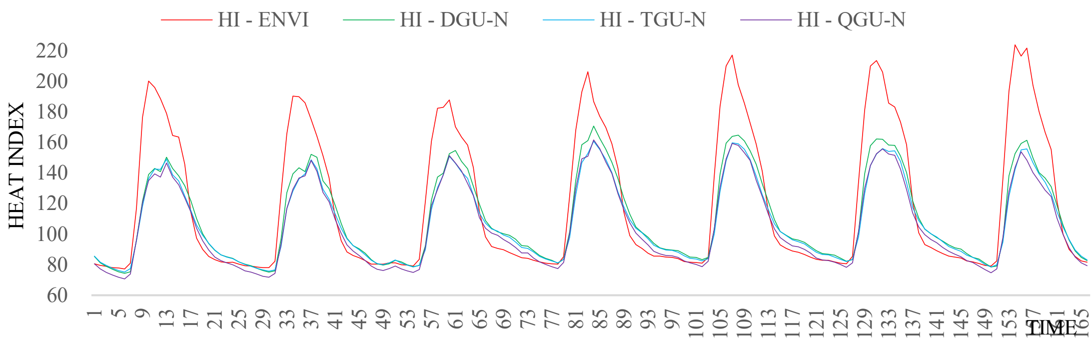


Figure 28 HI result of one week North

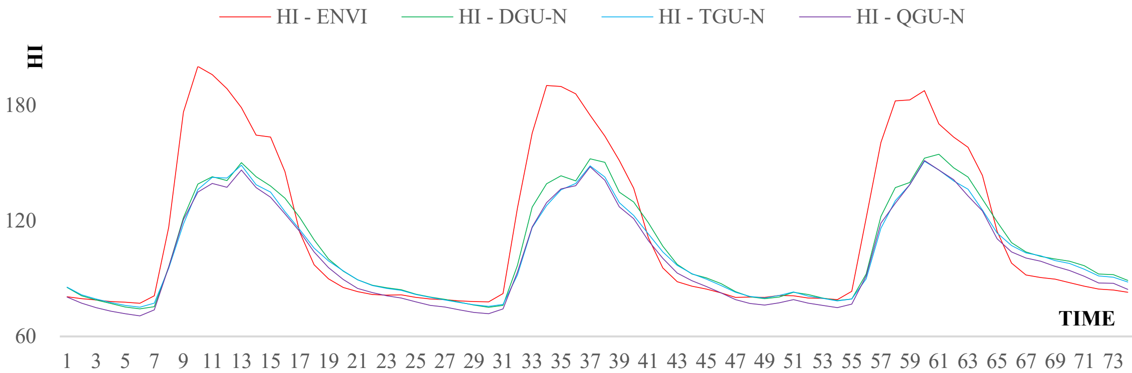


Figure 29 HI result for three Days

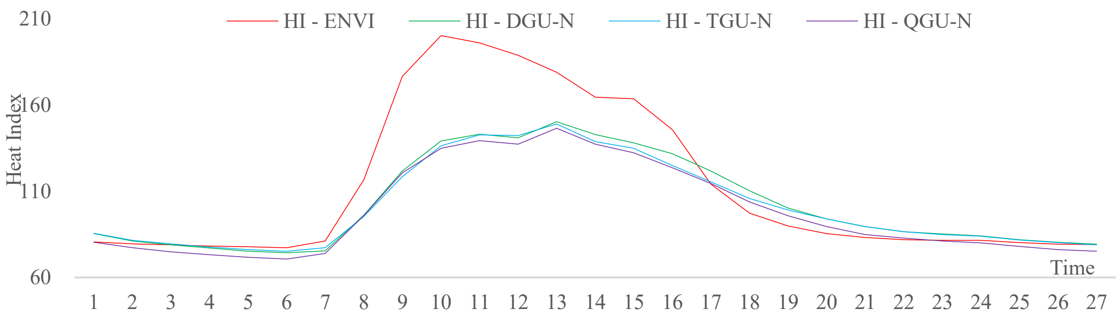


Figure 30 Heat index results ONE DAY at North

https://doi.org/10.54878/wvr24c41

The gaps between the performance values of the different glass types remained minimal between TGU & QGU. The time allocated for the function was less than recommended by other researchers; this means that an opportunity to pursue the study with greater depth regarding the other orientations in Dubai is required. Through a comprehensive analysis conducted over three days, Figure 30 details the HI results, with one day showing remarkable consistency in performances for QGU & TGU . The lowest indoor HI recorded by the QGU was followed by the TGU accordingly. In addition, a detailed examination of a single day reveals that the quad and triple configurations predominantly overlap in substantial segments.

The north direction made the DGU HI results closer to the environment, meaning the value of the differences between inside and outside is less (T_{EXT}-T_{INT}) as shown in Figure 30 which is for three days. It is moderate daylight that recedes and synchronizes with the ENV; thus, it constitutes a favorable choice for sunlight and energy efficiency. This makes it a financially economical selection for daylighting, particularly suitable for the summer months in Dubai. Figure 30 explicates this concept when scrutinizing a single day.

The supplementary layer enhances efficiency in the southern as QGU & northern as DGU during the summer months. The quad is getting of 8^{0}C less for indoor than outdoor environments during the daytime. TGU is between the QGU and parallel to the DGU, saving 5^{0}C for indoor rather than ENV during the daytime, which makes it economical for energy savings. The north being in shade aligns with SHGC, which requires another study outside of this paper.

Dubai experiences a few chilly nights during one week in December through the end of February. The advantages of the quad or triple system should be monitored considerably during the chilly times unless adequate balancing is provided from an interior perspective. In such cases, the quad system regains its efficacy by preventing heat loss. However, HVAC in Dubai is designed for better cooling. Looking closer at the gap between the ENV- HI and the other glazing types, results show that (QGU) defines a difference in the limit of 3 ^{0}C to 8 ^{0}C better than others. It becomes evident that the quad (QGU) outperforms both the double and triple configurations in terms of both variables, as shown in Figure 31. The HI integrates air temperature and humidity to gauge the perceived warmth experienced by the human body.

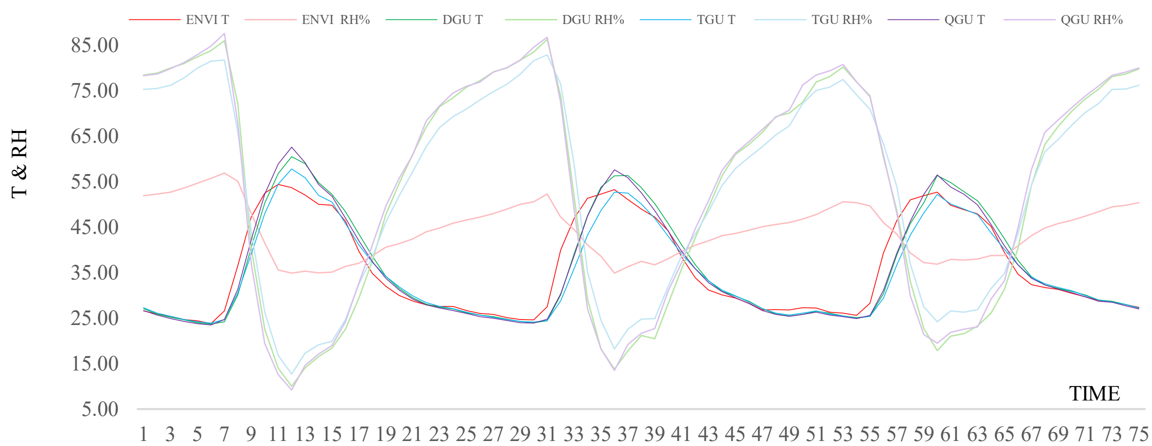


Figure 31 T & RH Three DAYS North

However, further analysis of the actual temperature revealed that triple (TGU) glazing is questionable. Quad (QGU) glazing improves performance during daylight hours, while the three glazing configurations overlap under nighttime conditions. Figure 31 shows a comparative analysis of the actual data recorded by HL, both indoors and outdoors, over a span of three days, thereby illustrating the complicated relationship of the QGU & TGU & DGU.

North orientation is favored according to the local codes. Architectural considerations to support better design, as office activity requires that orientation, as the major planning is possible to be fixed or in hand (Aksamija 2013). This demonstrates that advanced systems can replace outdated methods in managing various orientations by mixing different treatments as well required. Most city planning endeavors to optimize wind and solar access to enhance the urban environment with the goal of saving human comfort both indoors and outdoors.

The vast dataset comprising thousands of readings was organized using a Python program based on the results of the heat index. The concept operates by simply comparing the heat index results of the three glass units to those of the weather station located outside. Figure 32 illustrates the results functionality in a clear and transparent manner. The mathematical models delineate empirical data that corroborate the assertion that QGU demonstrates enhanced efficiency in terms of energy conservation. Further exploration of the quadruple system is necessary, as the findings are dependent on temporal and locational factors.

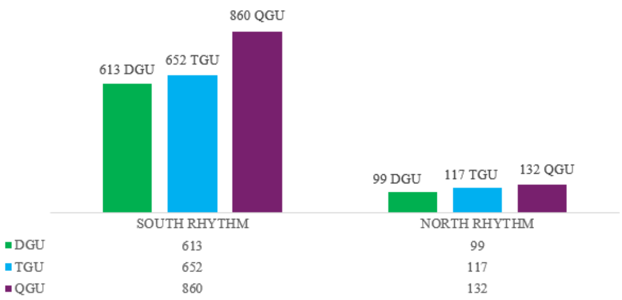


Figure 32 Python results shows QGU as best selection

The research using glass boxes to examine the indoor impact of various glazing types has demonstrated that (QGU) offers superior performance compared to both triple and double glazing, thereby signifying an advancement over traditional double-glazing systems. The results considered the quad system to be an upgrade that can be used for refurbishing old buildings with double glazing, for improving thermal performance, and for reducing noise.

5.4.The cooling load

The comparative analysis of the cooling load performance of double, triple, and quadruple glazing is conducted utilizing empirical data amassed from the summer season in Dubai (June 19 - September 30, 2024). All findings are standardized per square meter of glazing area, duly considering the U-value. By means of estimation, the annual conductive heat transfer through glazing (Wh) is calculated, taking into account cooling degree days (CDD) as 2508 (°C·day) with 23°C as economically recommended by DEWA in Dubai (Salem et al., 2022).The formula for calculating (Wh) is as follows:

(Wh) = Uw (W/m^2K) × Area (m^2) × CDD (°C·day) × 24 (h/day). Subsequently, the result is divided by 1000, while accounting for the coefficient of performance (COP) of split-unit air conditioning systems, valued as 3kw.(Kralj 2022,2023).

Table 9 estimation, the annual conductive heat transfer through glazing (W)			
Time 2024	DGU kWh/m^2	TGU kWh/m^2	QGU kWh/m^2
June 19-30	12.0	9.0	7.0
July	32.0	23.0	18.0
Auguest	33.0	25.0	19.0
September	27.0	20.0	16.0
All data presented is approximate, representing a rounded total as a fundamental estimation for the overall concept.			

The estimation based on 0.3-0.58 W/m^2k for QGU & TGU merely underscores that the quadruple (QGU) is diminishing the cooling demand to approximately 40% based on the available simple calculations for air conditioning.

6.Conclusion

This research aimed to mimic glass curtain walls in Dubai, focusing on types of glass and their orientation. The study analyzed three glass configurations within a glass box to determine the most sustainable option for Dubai's climate. The experiments used passive glass and heat loggers. The data were organized using a heat index equation and processed with a binary Python program and cooling load demand estimation.

The results were acceptable for the south-facing orientation. However, the efficacy was not as identical when facing north. The data from the south orientation leaned toward quad glazing due to a three-month testing period, whereas the north data were based on a two-week timeframe. A Python-based binary program with straightforward logic to extract insights from vast amounts of data indicates that quad glazing (QGU) exhibits superiority and was nearest to the ENV. All data presented in tables in CSV format and calculations are saved in the GitHub repository. The findings indicate that a quadruple-layer strategy performed more effectively in the southern region. In the northern area, where data were gathered over a two-week period, the results were complicated.

The findings indicate that employing a combination of diverse types of multi-layered glass exhibits varying degrees of energy efficiency, contingent upon the specific type, as well as the time and location. This implies that no single type of glass exhibits adequate efficiency to adapt to diverse environmental conditions. Notably, in Dubai, no project uses only one type of glass. The quality of quadruple glass is high, but it needs extra time to ensure its effectiveness. More quadruple glazing testing yields new advancements to reduce HVAC load by up to 50% based on experiments in Europe and the United States.

Recent developments in advanced materials are also paving the way for improvements in energy efficiency. Research indicates that integrating nanotechnology into window manufacturing can further enhance thermal performance, potentially minimizing energy consumption in buildings. Pilot projects in urban environments are underway to evaluate the real-world impact of these innovations on energy savings and comfort levels.

In Dubai, (QGU) glass VLT is modified and is less than (DGU) glass but can be used based on orientation in commercial or residential settings. Projects focus on aesthetics and energy efficiency due to DEWA restrictions on power consumption. Exceeding 350 kW threshold incurs costs for substation establishment. Architects must find passive ways to work around this limitation.

Moreover, the implementation of smart glass technologies is proving to be a game changer, allowing for dynamic control of heat and light transmission. This adaptability not only enhances user comfort but also reduces reliance on mechanical heating and cooling systems. Continued collaboration between architects, engineers, and materials scientists is shaping the future of sustainable building practices. By embracing these advancements, the industry is poised to achieve even greater reductions in carbon footprints while improving overall building envelope performance.

Acknowledgments

This paper acknowledges the invaluable support and funding provided by Hicorner Consultancy. Additionally, Engineer Abdullah Ihsan is credited with the design of the Python program and mathematical calculations.

The datasets pertinent to this research have been archived in a GitHub repository, with a few attached as an appendix.

Appendix

(HL) Data collected from four devices (35pages) with HI-EQ results for the glass box at south and north and Delta T results for 7 days south and north.

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