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Framework for optimising daylighting and passive indoor thermal comfort in single-banked office buildings in the temperate dry climate of Nigeria

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Abstract:
Many researchers have differed on the optimum values of Daylighting and Passive Indoor Thermal Comfort (DPITC) determinants in tropical climates. The study is aimed at developing a framework for optimising DPITC in singled-banked office buildings, during the activity period (8 a.m. to 5 p.m.), in the temperate dry climate of Nigeria. It was achieved by evaluating the effects of orientation, window-to-wall ratio (WWR), R-values of external wall insulation material, and shading devices on DPITC. A quantitative research design using an explorative design approach was employed in the study as well as an experimental research strategy through simulation method to optimise DPITC. The study used the Federal Secretariat building of Nigeria as a prototype of a single-banked office building. The Google SketchUp Pro 2022 and OpenStudio 3.3.0 simulation tools were used to evaluate the prototype building from January to December 2023. The data generated was analysed using relevant statistical tools (MANOVA, ANOVA, column charts, graphs, and tables). The findings revealed that the best WWR for daylighting and passive indoor thermal comfort are 20% and 15% respectively, while the compromise value was 20%. It was also noted that the R-value of the external wall insulation material does not affect the daylighting of an office building but affects the passive indoor thermal comfort, where the optimum R-value was of 3.26 m2·K/W. The mathematical model was developed as $A = 224.58 - 1254.84WWR + 102.87PF - 4.11R$ … ….1 where A is orientation, WWR window-to-wall ratio, PF projection factor, and R is the R-value of the external wall materials.

Keywords: daylighting, daylight autonomy, operative temperature, single-banked office building, thermal comfort

INTRODUCTION

Attaining adequate passive indoor environmental comfort particularly in multi-storey office buildings is critical to the success of a sustainable office building. It is crucial to take daylighting and passive indoor thermal comfort into account in their interactions (Zulkarnain et al., 2021; Zoure, Genovese, 2022) in tropical countries like Nigeria to avoid environmental pandemonium. For example, when a single comfort factor is considered independently, such as maximising the use of daylight when solar radiation levels are high, it may lead to an increase in indoor temperatures and cause thermal discomfort (Nasrollahzadeh, 2021). Recent studies conducted by Wang et al. (2024) and Chinazzo et al. (2019) indicated that there is a positive correlation between thermal comfort and the amount of daylight in a room. American National Standards Institute (ANSI) and American Society of Heating, Refrigerating and Air-conditioning Engineers (ASHRAE) Standard 55 (2020), as well as the International Organisation for Standardization (ISO) 7730 (2005) defined thermal comfort as the condition of mind that expresses satisfaction with the thermal environment. Daylighting is defined by Xue et al. (2014) as the people's satisfaction with the visual environment.

A study conducted by Zulkarnain et al. (2021) shows that daylighting is one of the elements that directly connects a building to its external surroundings and there are three types of daylight that can enter a building (Mohamed et al., 2020), these are: direct sunlight, diffused skylight, and light reflected from surrounding objects. Liu et al. (2023) noted that, the most significant type is the direct sunlight which enters the room through the openings. Researchers have indicated a number of factors affecting daylight performance as well as thermal comfort such as building orientation, type of window, and type of glass (Galal, 2018; Anthony et al., 2020). Another important factor is building spatial layout as observed by Musa (2023), Sasu et al. (2016), and St Clair (2009). Many studies in the tropics were able to predict daylight and thermal comfort but of conflicting values due to the failure to consider building spatial layout. For example: Mahmoudi Saber et al. (2015) findings were on the mixed-used buildings not tied to the basic building classification; Hakim et al. (2021) results were more aligning to single-banked buildings even though were silent on the building layout classification; while that of Salem Bahdad et al. (2022) did not consider a number of variables such as WWR, R-values of the materials as well as building layout. In addition to that, a study by Zhang and Ji (2022) have added a concept of energy without considering the building spatial layout, while Fan et al. (2023) findings were more applicable to open-plan office buildings than to other building layout classification though did not refer to the building layout.

This study aims at developing a framework of optimising daylighting and passive indoor thermal comfort (DPITC) in single-banked office buildings in the temperate dry climate of Nigeria. It was achieved by exploring the effects of window-to-wall ratio (WWR), orientation, overhang projection factor, and R-values of the exterior wall component of single-banked office buildings on DPITC in the temperate dry climate of Nigeria. These brought about the following research questions:

i. To what extent does the orientation (azimuth) affect DPITC of mid-rise office buildings?

ii. To what extent does the WWR affect DPITC of mid-rise office buildings?

iii. To what extent does the projection factor of a horizontal shading device affect the DPITC of mid-rise office buildings?

iv. To what extent do the R-values of the exterior wall component affect the DPITC of mid-rise office buildings?

Moreover, these also raised the following hypotheses: hypothesis (H_I) states that the effects of mean values of DPITC are significantly different for at least one of the azimuths in a single-banked office building in the temperate dry climate of Nigeria; hypothesis (H_2) states that the mean effects of DPITC are significantly different for at least one of the WWR in a single-banked building in the temperate dry climate of Nigeria; hypothesis (H_3) states that the mean effects of DPITC are significantly different for at least one of the overhang projection factors in a single-banked building in the temperate dry climate of Nigeria.

CONCEPT OF A FRAMEWORK

There are generally two types of frameworks: theoretical and conceptual frameworks as noted by Ravitch and Riggan (2017), and Kivunja (2018). Optimisation framework as defined by Al-Ansari and Alherbawi (2020) is the optimum technology that treats each waste type into useful products. The word “optimisation” in this research simply means to make the indoor environment of the office buildings as comfortable as it can be in the temperate dry climate of Nigeria. Sukreet and Kensek (2014) outlined four different types of optimisation in architectural education, which include: parametric analysis; genetic algorithms; multi-objective optimisation; and passive optimisation techniques. Passive optimisation is the process by which an expert designer generates a large number of design possibilities, typically with the use of simulation software, to meet optimisation standards. Sukreet and Kensek (2014) have critiqued the process of developing three or more building options, comparing them cognitively to past experiences, and then using intuition to choose the best one. Coello (2005) observed that a multi-objective algorithm is more traditionally associated with engineering and scientific fields. Parametric analysis is the process of changing the values of a particular variable until a maximum or minimum result is obtained which indicates the best solution. The research has adopted the parametric method of optimisation for achieving the study goal.

The climate type is a fundamental factor in optimising DPITC. A basic classification of climate can be of two categories based on different historical periods: classical and modern. The ancient Greeks used reasoning to categorise climate during the classical era. The creation and spread of weather recording equipment in the middle of the 19th century is credited with giving rise to modern climate classification. Although many different modern climate classifications have been developed, they may all be broadly divided into two categories: genetic climate classifications and empiric classifications (Arnfield, 2016; Ritter, 2019). The study has adopted the empiric climate classifications as widely adopted for all practical applications as concluded by Djamila (2018). Most climate classifications that are based on human comfort have their origin in Atkinson's (1953) climate classification (Koenigsberger et al., 2013) as shown by Musa (2022). The study has adopted Mobolade and Pourvahidi's (2020) climate classification based on the fact that it factored temperature, relative humidity, mean radiant temperature, and wind velocity in its method of classification. It also considered the gradual transition from one climatic zone to another as shown by Musa (2022).

MATERIALS, DATA AND METHODS

An experimental research strategy using a simulation method was employed through an exploratory design approach and quantitative research design. A non-convenience probability sampling technique was used in selecting the Federal Secretariat as an example of a single-banked office building as illustrated in Fig. 1. It was chosen for this study because its prototype is replicated all over Nigeria. The prototype was then modelled in Google SketchUp Pro 2022, Radiance from the OpenStudio 3.3.0 simulation tools.

Fig. 1. Federal Secretariat Abuja Nigeria. (Photo: Authors, 2024)

The window parameters used in the simulation were as follows: 3 mm thick glass as the window material of 0.331 solar transmittance at normal incidence; 0.6189 front side solar reflectance at normal incidence; 0.44 visible transmittance at normal incidence; 0.51 front side visible reflectance at normal incidence; and 0.0133 W/Mk conductivity. The simulation was from January to December 2023 on the hypothetical sites devoid of surrounding buildings and trees, in Jalingo, Minna, and Abuja, using the various range of values of WWR (15-40%), azimuths (0–270^0), overhang projection factor (0.35–0.6), and R-values (1.04–4.16m^2·K/W) and their corresponding mean values of Daylight Autonomy (DA), Useful Daylight Illuminance ($UDI_{100-3000}$), Spatial Daylight Autonomy (sDA), Operative Temperature (OT), and Relative Humidity (RH) was recorded. The methods used in conducting the research was based on the Kamel and Memari (2018), and IEA (2022) procedures. Based on these documents, the following steps were followed:

i. A prototype of Nigerian Federal Secretariat building was modelled in Google SketchUp 2017;

ii. In order to simulate daylight, EnergyPlus weather (EPW) was used as the type of weather file;

iii. SketchUp plugging known as OpenStudio was used to set weather files of Abuja, from weather Analytic;

iv. Radiance measure in OpenStudio was used for daylight;

v. Run period from January to December of 2023 was selected from Simulation settings;

vi. Simulation button was pressed for the final analysis.

Data generated were then analysed using the MANOVA statistical tool with a significance value of 0.05, bar charts, graphs, and tables. Regression analysis was also used to establish the relationship between the four variables in a single-banked office building for DPITC in the temperate dry climate of Nigeria.

RESULTS AND DISCUSSION

The results are presented based on the research questions earlier raised in this paper: To what extent does the azimuth angle affect DPITC of mid-rise office buildings in the temperate dry climate of Nigeria? The simulations of a single-banked office building with a WWR of 8.8%, and R-value of 2.08 m^2K/W was done, and the results are presented in Tab. 4.1 and 4.2. It was noted that three out of eleven conditions have fulfilled the benchmarks as put forward by Illuminating Engineering Society (IES, 2022) which recommended a DA of 60% of the work plane illuminance; $UDI_{100-3000}$ of 80%, and sDA of 75% in office space. It has also been observed that, as the azimuth angle increases the DA increases but UDI decreases. When the daylight indicators were ranked, it showed that a building oriented at zero degrees has the better daylighting as shown in Table 4.2. The finding is in agreement with the Anumah and Anumah (2007). The simulation results of the effects of building orientation on operative temperature and relative humidity are presented in Tab. 4.3.

Tab. 4.1. Simulation results of the effects of orientation on DA, sD, and UDI in mid-rise office buildings, in the temperate dry climate of Nigeria.

Azimuth	0^0	11.5^0	22.5^0	45^0	67.5^0	90^0
DA	73	73	73	75	76	76
sDA	97.5	97.4	97.4	97.7	97.5	97.5
UDI	81	80	79	74	69	67

(Source: Authors, 2024)

Tab. 4.2. Ranking of the daylight comfort metrics on building orientation.

Azimuth	DA	SDA	UDI	Daylight Comfort	Remark
0	3rd	2nd	1st	1st	0^0 is the best orientation to achieve daylighting
11.5	3rd	3rd	2nd	2nd	
22.5	3rd	3rd	3rd	4th	
45	2nd	1st	5th	6th	
67.5	1st	2nd	6th	8th	
90	1st	2nd	7th	9th	
112.5	1st	8th	6th	11th	
135	2nd	4th	5th	7th	
157.5	3rd	5th	3rd	5th	
180	3rd	6th	1st	3rd	
270	4th	7th	4th	10th	

(Source: Authors, 2024)

Tab. 4.3. Ranking of thermal comfort indicators for building orientation.

Azimuth	Operative temperature	Rank	Relative humidity	Rank
11.5	30.2825	1	64.125	1
0	30.32	2	63.85	2
22.5	30.37375	5	63.7375	3
45	30.77	4	63.125	4
67.5	31.13	5	62.6	5
90	31.295	6	59.7625	6

(Source: Authors, 2024)

Tab. 4.4. Ranking of the orientation for DPITC.

Azimuth	DA	SDA	UDI	Daylight Comfort	Thermal Comfort	DPITC	Remark
0	3rd	2nd	1st	1st	2nd	1st	11.5^0 is the most appropriate due to the effects of wind direction in the tropics.
11.5	3rd	3rd	2nd	2nd	1st	1st	
22.5	3rd	3rd	3rd	4th	3rd	2nd	
45	2nd	1st	5th	6th	4th	3rd	
67.5	1st	2nd	6th	8th	5th	4th	
90	1st	2nd	7th	9th	6th	5th	
112.5	1st	8th	6th	11th			
135	2nd	4th	5th	7th			
157.5	3rd	5th	3rd	5th			
180	3rd	6th	1st	3rd			
270	4th	7th	4th	10th			

(Source: Authors, 2024)

The result showed that 11.5^0 azimuth is the most appropriate orientation for better operative temperature and relative humidity. When values of daylight metrics and thermal comfort indicators were ranked together as indicated in Tab. 4.4. 11.5^0 was found to be the most appropriate for DPITC due to the direction of air circulation at 45^0 as observed by Szokolay (2008).

Hypothesis testing 1

H_{01}: There is no significant difference in DPITC among the mid-rise office buildings with different azimuth angles in the temperate dry climate of Nigeria.

One-way MANOVA was used to test if the effect of azimuth angle differs from one another significantly in one or more of the DPITC variables and a statistically significant difference was obtained, $F (25, 210) = 3.640$, $p < .00001$; Pillai's $\Lambda = 1.512$, partial $\eta 2 = 0.302$. Hence since there were more than two (2) levels of the independent variable, there was a need to determine where the differences truly came from, which brought about the need for a post-hoc test. A series of one-way ANOVAs on each of the DPITC variables was conducted as a follow-up test to the MANOVA. The results turned out to be statistically significant in all the five DPITC variables: DA *(F (5, 42) = 14.645; p < .000; partial η2 = 0.635),* UDI *(F (5, 42) = 419.750; p < .0000; partial η2 =0 .980),* $_S$DA *(F (5, 42) = 3.267; p < .014; partial η2 = 0.280),* mean annual operative temperature ($F(5, 42) = 10.776$; $p < .000$; partial $\eta^2 = .562$), and mean annual relative humidity ($F(5, 42) = 2.857$; $p < .026$; partial $\eta^2 = 0 .254$).

A series of post-hoc analyses using Fisher's LSD were conducted to examine individual mean differences comparison across the azimuth angles and DPITC variables. The results revealed that: except for azimuth 45^0, all DA were statistically significant with one another for all values that were greater than 22.5^0 but less than 45^0; except for the relationship between azimuth 0^0 and 11.5^0, all UDI values were statistically significant to one another; and finally, except for the relationship between azimuth 22.5^0 and 45^0, 67.5^0 and 90^0, all $_S$DA values were not statistically significant to one another. That means all azimuth angles that are within 45^0 are not statistically significant to one another, while those that are not within the same 45^0 are statistically significant to one another. For example, 0^0, 11.5^0, and 22.5^0 are not significant to one another, while they are significant with 45, 67.5^0, and 90^0. The reverse is also true. For the relative humidity, it shows that, except azimuth 90^0 which was statistically significant to all others, all the average annual relative humidity values were not statistically significant to one another.

To what extent does the WWR affect DPITC in mid-rise office buildings in the temperate dry climate of Nigeria? The simulations of a single-banked office building, with an R-value of 2.08 m^2K/W and a constant Azimuth angle of 11.5^0 were done and the results are presented in Tabs. 4.5, 4.6, and 4.7. To evaluate the most appropriate WWR for optimum daylighting, the rank and percentile were used, and the results showed that 20% is the optimum value of WWR for daylighting in the temperate dry climate of Nigeria, which has complied with Shebl (2007) and ASHRAE 90.1 (Goel et al. 2014). However, it is contrary to the 2012 International Energy Conservation Code (IEA, 2019) which recommends a different value of 30% (Makela et al., 2011).

The simulation results of the effects of WWR on operative temperature and relative humidity are presented in Tabs. 4.6 and 4.7. The results showed that while relative humidity has met the condition recommended by ASHRAE Standard 55 (2020) as shown in Tab. 4.7, none of the operative temperatures met with the ANSI/ASHRAE Standard 55 (2020) as indicated in Tab. 4.6. The rank and percentile were used to reveal the best WWR for minimum operative temperature and maximum relative humidity and 15% was found to be the most appropriate WWR for better operative temperature as well as relative humidity as indicated in Tab. 4.8. When the values of daylight metrics and thermal comfort indicators were ranked together as indicated in Table 4.8, 20% WWR was found to be the most appropriate for DPITC. The finding has confirmed that of Budhiyanto (2017).

Tab. 4.5. Simulation results for the effects of WWR on DA, $_S$DA and UDI in a mid-rise office building, in the temperate dry climate of Nigeria.

WWR	0.15	0.195	0.200	0.220	0.240	0.300	0.400
DA	71	80	80	81	82	84	84
UDI	82	79	79	77	75	68	53
$_S$DA	94.04	95.64	95.71	96.25	96.39	96.93	97.5

(Source: Authors, 2024)

Tab. 4.6. Simulation results for the effects of WWR on the operative temperature of the prototype mid-rise office building, in the temperate dry climate of Nigeria.

	WWR						
	0.15	0.195	0.2	0.22	0.24	0.3	0.4
Room	Average RH	Average RH	Average RH	Average RH	Average RH	Average RH	Average RH
102	27.3	29.3	29.3	29.54	29.9	30.74	28.46
202	31.47	32.19	32.43	32.55	32.79	33.63	33.63
302	31.83	32.43	32.43	32.91	33.15	33.87	33.63
402	31.95	32.43	32.67	32.91	33.15	33.87	33.87
502	31.95	32.43	32.91	32.67	33.39	34.11	34.35
602	31.71	32.67	33.15	32.79	33.63	34.11	33.87
702	31.95	32.79	32.55	32.91	33.15	34.11	33.87
802	32.07	32.43	32.43	32.91	33.15	34.35	33.99
Average	31.27875	32.08375	32.23375	32.39875	32.78875	33.59875	33.20875

(Source: Authors, 2024)

Tab. 4.7. Simulation results of the effects of WWR on the relative humidity in the temperate dry climate of Nigeria.

	WWR						
	0.15	0.195	0.2	0.22	0.24	0.3	0.4
Office	Average RH	Average RH	Average RH	Average RH	Average RH	Average RH	Average RH
102	65.25	65.25	65.5	65.25	65.5	65.25	62.5
202	61.5	60.5	60.1	60.25	59.5	59	52.3
302	62.1	60.1	60.25	59.58	59.5	59	52.2
402	56.3	54	54	54	54	54	50.5
502	59.5	57.75	57.75	57.75	57.5	56	53.3
602	56.3	54.5	54	54.5	54.25	56	52.1
702	59.2	57.75	57	57.25	57.25	56	53.3
802	60.5	60.25	60.25	60.1	60.5	58	55.2
Average	60.08125	58.7625	58.60625	58.585	58.5	57.91	53.925

(Source: Authors, 2024)

Tab. 4.8. Ranking of the WWR for DPITC.

WWR	DA	UDI	sDA	Daylight Comfort	Thermal Comfort	DPITC	Remark
15	5th	1st	7th	6th	1st	4th	
19.5	4th	2nd	6th	2nd	2nd	2nd	
20	4th	2nd	5th	1st	3rd	1st	
22	3rd	3rd	4th	3rd	4th	3rd	20% is the most appropriate WWR for DPITC.
24	2nd	4th	3rd	4th	5th	5th	
30	1st	5th	2nd	5th	6th	6th	
40	1st	6th	1st	7th	6th	7th	

(Source: Authors, 2024)

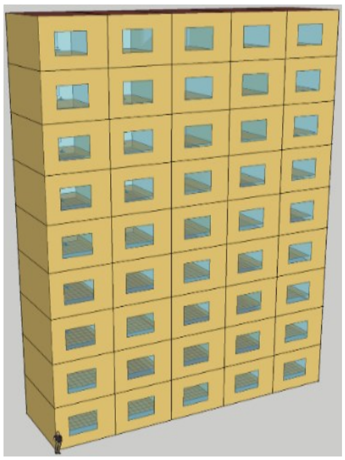

Fig. 2. Simulation of Federal Secretariat Abuja. (Source: Authors, 2024)

Hypothesis testing 2

H2: It states that the mean effects of DPITC are significantly different for at least one of the WWRs in a single-banked building in the temperate dry climate of Nigeria.

The one-way MANOVA was used to test if the mid-rise office buildings with different WWRs differ from each other significantly in one or more DPITC variables. It was tested and a statistically significant difference was obtained, F (30, 210) = 8.634, p < .0000; Pillai's Λ = 2.761, partial η2 = 0.552 A Series of one-way ANOVA's on each of the DPITC variables was conducted as a follow-up test to the MANOVA. The results turn out to be statistically significant in all the DA *(F (6, 42) = 59.39; p < .0000; partial η2 =0 .895)*, UDI *(F (6, 42) = 271.793; p < .0000; partial η2 = 0.975)*, and sDA *(F (6, 42) = 66.778; p < .0000; partial η2 = 0.905)*. The other two were not, because they have fallen out of the span of -2 to +2 as the acceptable values for skewness and kurtosis, as specified by George and Mallery (2010).

A series of post-hoc analysis using Fisher's LSD were performed to examine individual mean differences comparison across all the seven different WWR and five DPITC variables. The results revealed that, for DA, UDI, and sDA, all WWRs were statistically significant with one another, and the opposite was also true for operative temperature and relative humidity because they were nonparametric data. A Kruskal-Wallis test was therefore used to compare the effects of WWR on operative temperature having fallen out the span of -2 to +2 as the acceptable values for skewness and kurtosis, as specified by George and Mallery (2010). It showed a statistically significant difference in operative temperature score among the different WWR, χ2(5) = 29.62, p = 0.0000, with a mean rank Operative temperature of 9.75 for 0.15 WWR, 16.69 for 0.195 WWR, 22.63 for 0.2 WWR, 26.94 for 0.22 WWR, 33.94 for 0.24 WWR, 45.13 for 0.3, and 42.44 for 0.4 WWR.

To what extent does the shading device affect the DPITC of mid-rise office buildings in the temperate dry climate of Nigeria? The simulations of a single-banked office building, with an R-value of 2.08 m^2K/W, azimuth angle of 11.5^0, a shade offset value of 0.3, and WWR of 20%, were done and the results are presented in Fig. 2. The finding showed that the optimum projection factor for daylighting in mid-rise office buildings in the temperate dry climate is 0.35 followed by 0.45/0.5, and lastly 0.6 as indicated in Fig. 3. The simulation results showing the effects of the projection factor on thermal comfort show that, while relative humidity has met with the recommended values given by ASHRAE Standard 55 (2020), none of the operative temperatures has met the ANSI/ASHRAE Standard 55 (2020) as shown in Fig. 4.

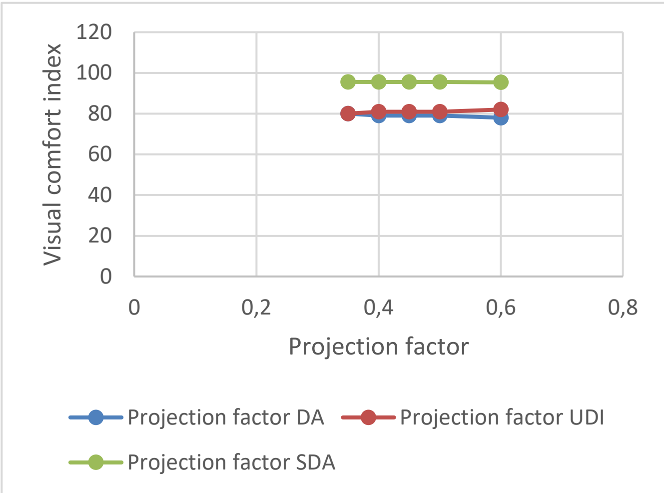

Fig. 3. Projection factor for optimum daylighting in a single-banked office building in temperate dry climate of Nigeria. (Source: Authors, 2024)

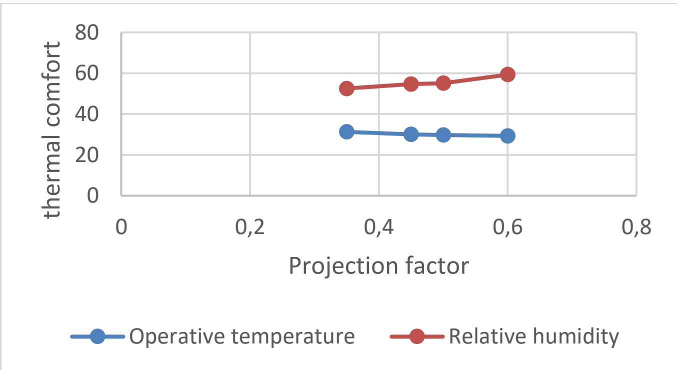

Fig. 4. Projection factor for minimum operative temperature and relative humidity in a single-banked office building. (Source: Authors, 2024)

To reveal the appropriate projection factor for minimum operative temperature and maximum relative humidity, the rank and percentile were used, and the results were obtained as presented in Fig. 4. The result showed that 0.6 was the most appropriate projection factor for better operative temperature as well as relative humidity. When the values of daylight metrics and thermal comfort indicators were ranked together as indicated in Tab. 4.9. 0.5 and 0.6 projection factors were found to be the most appropriate for DPITC. The finding was almost in conformity with that of Hien and Istiadji (2003), who discovered 0.55 as the most effective shading coefficient for passive indoor comfort.

Tab. 4.9. Ranking of the projection factor (PF) for DPITC.

Projection factors	DA	UDI	sDA	Daylight comfort	Thermal comfort	DPITC	Remark
0.35	1st	3rd	1st	1st	4th	4th	0.5 and 0.6 are the most appropriate PFs for DPITC but a level of significance is required to resolve it.
0.45	2nd	2nd	2nd	2nd	3rd	3rd	
0.5	2nd	2nd	2nd	2nd	2nd	1st	
0.6	3rd	1st	3rd	3rd	1st	1st	

(Source: Authors, 2024)

Hypothesis Testing 3

H03: There is no significant difference in DPITC between mid-rise office buildings with different projection factors of shading devices in the temperate dry climate of Nigeria.

The MANOVA test was conducted to test if there would be one or more differences between PF and DPITC variables and a statistically significant difference was obtained, F (20, 116) = 2.487, p < .001; Pillai's Λ = 1.200, partial η2 = 0.300. A homogeneity for variance assumptions was tested for all the five DPITC variables before conducting a series of tests between the subject effects. Based on a series of Levene's F tests, it was considered satisfactory. A series of one-way ANOVAs on each of the five DPITC variables was conducted as a follow-up test to the MANOVA. The results turned out to be statistically significant in all the DA *(F (4, 30) = 3.265; p < .025; partial η2 =0 .303),* UDI *(F (4, 30) = 10.466; p < .0000; partial η2 = 0.583),* SDA *(F (4, 30) = 4.500; p < .006; partial η2 = .375) and Operative temperature (F (4, 30) = 2.843; p < .041; partial η2 = 0.275).*

A series of post-hoc analysis using Fisher's LSD were performed to examine individual mean differences comparison across all the five different PF and five DPITC variables. The results showed that 0.5 and 0.6 have almost equal statistically significant differences with others, and therefore 0.5 PF is chosen for economic reasons. For example, the mean scores for UDI were statistically significantly different between 0.6 PF and 0.35 PF (p < .05), 0.6 PF and 0.4 PF (p < .05), 0.6 PF and 0.45 PF (p < .05), 0.6 PF and 0.5PF (p < .05), and 0.6 PF and 0.6 PF (p < .05); while the mean scores for UDI were statistically significantly different between 0.5 PF and 0.35PF (p < .05), 0.5 PF and 0.4PF (p < .05), 0.5 PF and 0.5PF (p < .05), and 0.5 PF and 0.6PF (p < .05), but not between 0.5 PF and 0.45PF (p < .249). The result has also revealed that UDI responds to PF more than the other four variables.

To what extent do the R-values of the exterior wall insulation material affect DPITC of mid-rise office buildings in the temperate dry climate of Nigeria? The simulations of a single-banked office building, with an azimuth angle of 11.5^0, a shade offset value of 0.3, an overhang projection factor of 0.5, and WWR of 20% were done and the results are presented in Tab. 4.10. The findings have shown that all four conditions were the same and, therefore, the R-value of external wall insulation material does not affect the daylighting of an office building as indicated in Tab. 4.10. The simulation results of the effect of R-values of external wall insulation material on thermal comfort are presented in Fig. 5. The results have shown that only one of the operative temperatures has met the ANSI/ASHRAE Standard 55 (2020) (whose R=4.16). It has also been observed that as the R-value of external wall insulation materials increases the thermal comfort also increases.

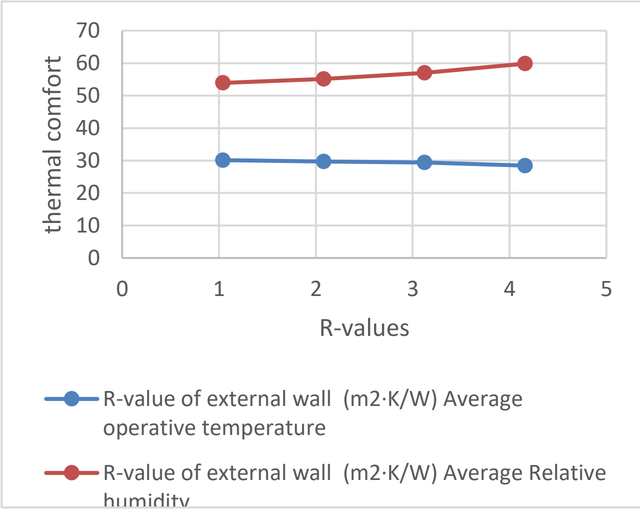

Fig. 5. R-values of external wall materials for minimum Operative temperature and Relative humidity in a single-banked office building. (Source: Authors, 2024)

To reveal the appropriate R-value of external wall insulation material for the mean value of operative temperature and relative humidity, the rank and percentile were used, and the result showed that, as the R-value increases, the thermal comfort also increases as indicated in Figure 4.10. Correlation equations: - *RH = 1.8882R + 51.569,* and *T = -0.5106R + 30.77* (where *RH is relative humidity, R is* R-value, and T is operative temperature*)* for relative humidity and operative temperature revealed the most appropriate R-value for better operative temperature as well as relative humidity was 3.26 m2·K/W. When the values of daylight metrics and thermal comfort indicators were ranked together, 3.26 m2·K/W was found to be the most optimised R-value for DPITC as indicated in Tab. 4.11. The result conformed with that of ANSI/ASHRAE/IES Standard 90.1 (2010 and 2017 editions) which recommended a minimum range of R-value of 1.0–2.7 (m2·K/W) for non-residential buildings but contrary to that of Energy Conservation Building Code (2014), which recommended the optimum R-value of 3.7 (m^2·K/W) as the optimum for non-residential buildings.

Tab. 4.10. Ranking of the DA, sDA, and UDI against the R-value of external wall insulation materials.

R-value of the external wall (m2·K/W)	DA	RANK	UDI	Rank	sDA	Rank	Daylight rank
1.04	79	1	81	1st	95.5	1	1
2.08	79	1	81	1st	95.5	1	1
3.12	79	1	81	1st	95.5	1	1
4.16	79	1	81	1st	95.5	1	1

(Source: Authors, 2024)

Tab. 4.11. Ranking of the R-values for DPITC. Remark: 3.26 m2·K/W is the most appropriate R-Value of the external wall for DPITC in the temperate dry climate of Nigeria.

R-Value of external insulated wall material (m2·K/W)	DA	UDI	sDA	Daylight Comfort	Thermal Comfort	DPITC

1.04	1	1	1	1	4	4
2.08	1	1	1	1	3	3
3.12	1	1	1	1	2	2
4.16	1	1	1	1	1	1

(Source: Authors, 2024)

Hypothesis testing 4

The homogeneity of variance-covariance matrices was tested using Box's Test of Equality of Covariance Matrices and Box's M value obtained is 3.494 with a p-value of .963, which was interpreted as non-significant based on Huberty and Petosky's (2000) guidelines. Therefore, the covariance matrices of the dependent variables were equal across groups for MANOVA. The one-way MANOVA was tested, and a statistically significant difference was obtained, F (3, 28) = 3.168, p < .040; Roy's Largest Root Λ = .339, partial η2 = .253. A homogeneity for variance assumptions was tested for all thermal comfort variables before conducting a series of tests between the subject effects. Based on a series of Levene's F tests, it was considered satisfactory. A series of one-way ANOVAs on each of the two thermal comfort variables was conducted as a follow-up test to the MANOVA. The results turned out to be statistically significant in all the Average Annual Operative Temperature *(F (3, 28) = 3.014; p < .047; partial η2 = .244) and Average Annual Relative Humidity (F (3, 28) = 2.936; p < .051; partial η2 = .239).* A series of post-hoc analyses using Fisher's LSD was performed to examine individual mean differences comparison across all the two different R-values and four thermal comfort variables. The result revealed that there is a statistically significant difference in the relationship between 4.16 and 2.08/ 1.08 for Average Annual Relative Humidity than in any other ones and between 4.16 and 2.08 in Average Annual Operative Temperature.

Mathematical models

These were applied to develop a relationship between the optimised DPITC determinants for single-banked office buildings in the temperate dry climatic zone of Nigeria. The mathematical model is limited to office buildings with horizontal shading devices, for it is more effective than the vertical in the tropics as observed by Al-Tamimi (2011) and Kim et al. (2013). The framework was used to obtain four more optimised DPITC values in each type of office building as indicated in Tab. 4.12 for single-banked office buildings. It was used to carry out the multiple regression to investigate whether the optimised values of WWR, projection factor, and R-value of external wall material could significantly predict different optimised azimuth angles for DPITC in single-banked office buildings in a temperate dry climate of Nigeria. The results of the regression indicated that the model explained 99.9% of the variance and that the model was a significant predictor of azimuths, F(3,1) = 4700.8, p = .010721. The WWR, projection factor (PF), and R-value of external wall materials (R) contributed significantly to the model (B = -1254.84, p=0.010872), (B = 102.8743, p=0.017526), and (B = -4.10695, p=0.044915), respectively.

Tab. 4.12. Five sets of optimised values of DPITC in single-banked office buildings in a temperate dry climate.

S/NO	Azimuth	WWR	PF	R-value
1	11.5	0.2	0.5	3.26
2	22.5	0.2	0.6	3.12
3	35	0.15	0.07	2.08
4	45	0.15	0.25	4.16
5	12.5	0.2	0.5	3.1

(Source: Authors, 2024)

$Y = C + M1X1 + M2X2 + M3X3 \dots\dots..4.1$

The 4.1 formula was used to develop the model from regression results as follows:

Azimuth (A)= 224.5802 + (-1254.84 x WWR) + (102.8743 X Projection Factor) + (-4.10695 x R-Value)

A= 224.58 - 1254.84WWR + 102.87PF - 4.11R…….4.2

SI Units: A= (0); R= (m^2.K/W); C= (0); M1= (0); M2= (0); and M3=(0 W/m^2.K).

DISCUSSION AND CONCLUSION

The research has found out that, for a building to have optimum passive indoor thermal and adequate daylight, the values of azimuth, WWR, overhang projection factor and R-value of the external wall materials must comply with the following equation: A= 224.58 - 1254.84WWR + 102.87PF - 4.11R…….4.2 for example, if a building is oriented along recommended azimuth of 11.5^0 then its WWR, overhang projection factor and R-value of the external wall materials must be 20%, 0.5 and 3.26 m2·K/W respectively. The findings have confirmed the observation of Ochedi and Taki (2022) that no single orientation is suitable for all buildings in a climate zone.

The result has explained the reasons why there are many differences in WWR, R-value, orientation and overhang projection factors by various researchers. For example, since Al-Tamimi, (2011), Anumah and Anumah (2017), Odunfa et al. (2018), Shebl (2007), and ASHRAE 90.1 (Goel et al. 2014) used similar azimuths, R-value and shadings, they recommended similar WWR. However, 2012 International Energy Conservation Code (IEA, 2019) recommended different WWR for it used different values of azimuth, shadings, and R-value of external wall material. Another important factor is the building spatial layout which may be the reason ANSI/ASHRAE/IES Standard 90.1 (2010 and 2017 editions) recommended a minimum range of R-value between 1.0 to 2.7 (m2·K/W) for non-residential buildings contrary to that of Energy Conservation Building Code (Bureau of Energy, 2017), which recommends 3.7 (m2·K/W).

Therefore, the architects and other building professionals should not mix the values of building considerations from different researchers for each might have used different determinants. Typical example are Kandar et al. (2011) and SOLID GREEN (2017) who used different building spatial layout and arrived at their different values.

Framework validation

It is very important to engage the users in the validation of any framework, as noted by Fan et al. (2023). There are various ways of validating a model which include: an expert assessment validation and the examination of framework output for reasonableness under a variety of settings of the input parameters.

Examination of framework output under a variety of settings of the input parameters

This involved changing the values of one of the framework concepts such as WWR, R-values, or PF, which may affect the values of other concepts, to achieve the optimum passive thermal and daylighting of an office building.

Testing the values given by the Building Code of Australia (BCA) and Australia's guide to environmentally sustainable homes (AGESH)

The study tested the values given by BCA and AGESH, which recommend the optimum WWR as 19%, orientation as 11⁰NE, minimum R-values as 2.8 m2.K/W, and projection factor as 0.35. The result complied with $A = 224.58 - 1254.84WWR + 102.87PF - 4.11R$.

Testing the values given by ASHRAE standards

The study tested the values given by ASHRAE, which recommended the optimum value of WWR as 20%, minimum R-values as 2.68 m^2.K/W, and projection factor as 0.5 (except if WWR was greater than 30%). The result complied with $A = 224.58 - 1254.84WWR + 102.87PF - 4.11R$ and McGee (2013) findings, proposed an optimum orientation of up to 15° NE.

Testing the values given by the International Energy Conservation Code (IECC)

The study tested the values given by IECC which recommended 30% as the maximum WWR, 3.52 m^2.K/W as the maximum value of R, 15^0 optimum azimuth angle, and 0.6 as the projection factor. The result complied with $A = 224.58 - 1254.84WWR + 102.87PF - 4.11R$.

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