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# Application of Fuzzy Logic Approach via GIS for Determining the Optimum Groundwater Wells Sites Based on the Hydro-Geoelectric Parameters

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## ABSTRACT

Salah Al-Din Governorate, including the study area located in Baiji district, is considered an important agricultural area in Iraq. As these areas have become mainly dependent on ground water. As this led to the depletion of underground water reservoirs, which turned many of the wells into unproductive or poorly productive wells. Therefore, there was a need to re-evaluate the hydraulic properties in the region, and then nominate sites for drilling new wells with high productivity according to the data of this evaluation. Selecting new well sites is becoming an increasingly difficult task. All hydraulic properties and geological factors must be taken into consideration. On the other hand, GIS technology is considered one of the most reliable techniques used in the process of determining the most appropriate sites. All this is done according to the use of algorithms that depend mainly on the importance of each factor and dealing with it as a class within the selection and nomination mechanism. In this study, fuzzy logic was applied through geographic information systems technology to determine the optimum sites for new well drilling with high productivity, based on the analysis of hydro-electrical parameters of the aquifer in the region. The research region was divided into four groups by the findings map: excluded, low suitability, moderate suitability, and high suitability. The area for each suitability category was 172.53, 269.76, 131.89, 127.26 km$^2$ respectively.

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## 1. Introduction

Groundwater is an important and basic resource of the national wealth (Aretouyap et al., 2022; Abdulrazzaq et al., 2022a), and it is included in the process of human and economic development (Aladeboyeje et al., 2021; Abdulrazzaq et al., 2022b). The groundwater in Iraq is also a vital tributary to confront the shortage of surface water (Abdulrazzaq et al., 2020a), as Iraq's repeated losses from the waters of the Tigris and Euphrates rivers and their tributaries have reached frightening degrees in recent years, which has had a negative impact on the agricultural, industrial and other sectors (Abdulrazzaq, 2011). The fluctuation and irregularity of rainfall led to the transformation of large areas of land into arid areas and alarming levels that portend a dangerous future if they are not addressed by comprehensive scientific and strategic plans.

The impacts of policies made by the decision in the water industry are not confined to financial implications alone, but also encompass, with equal weight, circumstances for human safety, health, and survival, as well as the economic and social characteristics linked with these conditions, as most countries depend on this water as a water source that meets Sometimes 90% of their water needs, especially the countries of the Arab region, specifically countries devoid of surface water sources and with a desert climate. People's needs for water are increasing with the increase in industrial, agricultural and urban progress, which has made most countries' attention lately to water (Al-Janabi, 2008), and as it is It is known that the water resources available for use are constantly decreasing as a result of the increasing rates of increasing demand for water, and therefore it has become necessary to expand studies and research in the detection and investment of groundwater, which requires various investigations for the purpose of identifying the underground aquifer and how to renew it and the method of extraction. Water-bearing rock units called aquifers (Todd, 1980). A water aquifer is a formation or group of geological formations with good permeability and porosity, saturated with water, and having the ability to pass economic quantities of water through springs or wells (Walton, 1970).

Arbitrary water well drilling, on the other hand, may result in aquifer degradation when it is not conducted in accordance with a well-thought-out plan for identifying suitable well exploration locations with high productivity. As a result, a strategy for selecting well locations in order to maximize groundwater development should be devised. The ability to create a plan for locating suitable drilling places is mostly reliant on specific factors that reflect the quality and quantity of groundwater that may be extracted from the aquifer. Geoelectrical measures are used in this context to quantify the thickness and depth of the aquifer, as well as to evaluate water quality and other factors that may be estimated using these observations. Several criteria can also be integrated utilizing modern GIS software and the Multi-Criteria Evaluation (MCE) approach to discover potential drilling sites. GIS is a geographic database management system for managing data from a variety of sources. It's a useful tool for site selection studies since it stores, analyzes, and presents data according to user-defined criteria (Abdulrazzaq et al., 2020b). The MCE methodology is a decision-making method that integrates qualitative and quantitative data by dissecting it in a systematic sequence and using numerous criteria (Chan et al., 2008; Nakamo, 2021).

The fuzzy model has been proven operative for such hydrological surveys. Shao et al. (2020) recognized groundwater potential zones in semi-arid Shanxi Province (China) using the fuzzy algebraic model. Pathak and Bhandary (2020) used a multi-layer fuzzy inference system in a GIS to assess groundwater vulnerability Mallik et al. (2021) analyzed groundwater suitability for drinking using GIS-based fuzzy model.
The goal of this project is to use the MCE approach with GIS as a decision-making tool to choice the best drilling site for new wells. The hydro-geophysical characteristics produced from the vertical electrical soundings (VES) data are used to choose the best locations. The findings of this study have applications in groundwater management, as well as agricultural, livestock, and human livelihoods.

## 2. Study Area

### *2.1 The Location of the Study Area*

The study area is located within Salah al-Din Governorate between the city of Baiji in the north and Tikrit in the south, along the western bank of the Tigris River (Figure 1), between longitudes 43° 40' - 43° 56' and latitudes 34° 35' - 34° 54'. It is bordered from the east by the Tigris River, from the west by Tikrit Subsurface Anticline (TSA), from the south by Wadi Sheshin, and the sand dunes from the north and northwest. The area is semi-rectangular, with a length of about 45 km, and a total area of about 700 km$^2$.

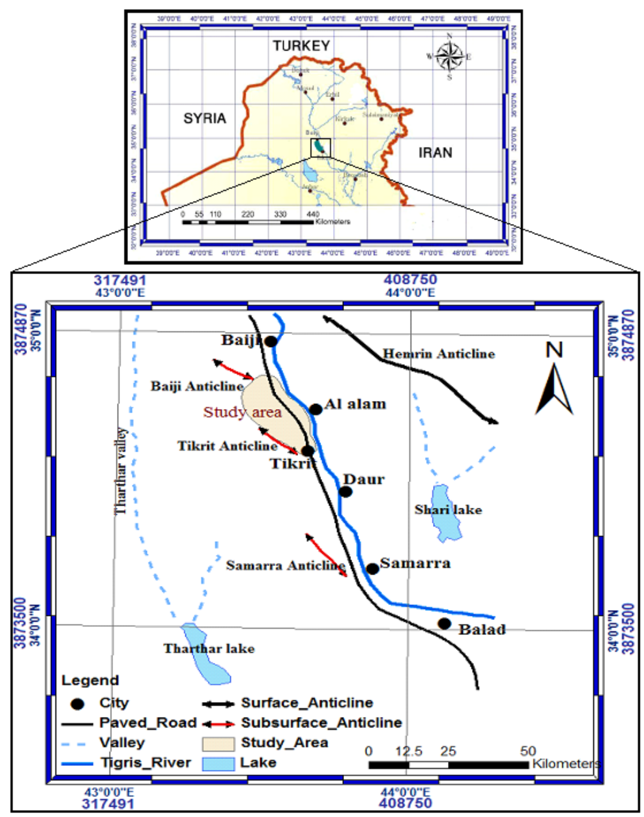


**Figure 1.** A site map of the study area

### *2.2 The Topographic and Tectonic Setting*

The area is generally flat, with a few ripples for some small valleys that head to the east and southeast towards the Tigris River. A major portion of the research region is covered by river terraces, about two-thirds of the area, and they are covered with gypsum soil with gravel. As for the heights of the earth's surface, they range from 160 meters above sea level at its western borders near the TSA and descend eastward towards the Tigris River until they reach 100 meters at the river bank. The geomorphology and topography of the region in general are related to its geological and structural situation, in addition to the processes of erosion and weathering (Al-Ani, 1997). Among the most important geomorphological phenomena observed in the region are valleys, as the region is characterized by the presence of two types of valley systems and several ranks up to the fifth level, in which seasonal rainwater flows, the first is known as the tree system and the second is known as the parallel system. The density of these valleys increases in the western part of the region near the TSA, which is in the form of a dense superficial drainage system that heads towards the east and then deviates towards and south-east to drain into Wadi Sheshin and then into the Tigris River. These valleys are characterized by a slight slope, filled with fine-grained calcareous deposits. As for the northern and northwestern part, it is characterized by the lack of valleys that end with flood depressions inside the region, in which rains gather in the form of valleys that greatly help in replenishing the groundwater (Al-Jubouri, 2011). A number of small valleys stretch from the boundaries of the river terraces and head east towards the Tigris River in the eastern half of the area next to the Tigris River. The flow of the minor valleys switches direction to the west in the west of Tikrit's subsurface fold, which marks the region's southwestern boundary. The presence of cliffs and the mass destruction of cliffs along the Tigris River, as well as the presence of sand dunes and sand plates, are among the other geomorphological occurrences (Al-Ani, 1997).

### *2.3 Geological Setting*

The exposed rocks in the region range in age from the middle Miocene to Quaternary deposits. The Injana Formation, which is exposed in the northern portion of the research region as illustrated in Figure 2, is the oldest exposed formation in the region. It also unfolds in Wadi Sheshin, which represents the southern boundary of the study area. The age of this formation is the late Miocene, and the formation is divided into two main members, the first one (Lower member) is consists of alternating layers of mudstone, siltstone and sandstone, where the second member (Upper member) is consists of alternating fractured sandstone and mudstone layers and siltstone layers of little thickness. Quaternary deposits also cover a large area of the study area that divided into two parts (Pleistocene and Holocene). Pleistocene sediments is consists mainly of gravel deposits represented by river terraces deposits, as well as other deposits such as gypsum soil (Gybkarite). Gravel deposits comprise a substantial portion of the research area, the gravel varies in size from boulders to gravel, and it is poorly interconnected, which led to the creation of a good layer for water penetration into the aquifers (Al-Ani, 1997). The sedimentary facies of these assemblies were divided into four facies, namely (mud pebbles, sandy clay pebbles, sandy pebbles, and sandy clay pebbles) (Basi & Karim, 1990). Gypsum soil, on the other hand, covers a considerable portion of the land and contains gravel, sand, silt, and clay deposits, and it is rich in secondary gypsum, and is classified as gypsum facilitation. Holocene sediments is consists of fine sediments group from different sources, as like Flood plain deposits, Valley and depression fill deposits (Al-Janabi, 2008), and Aeolian deposits (Jassim & Goff, 2006).

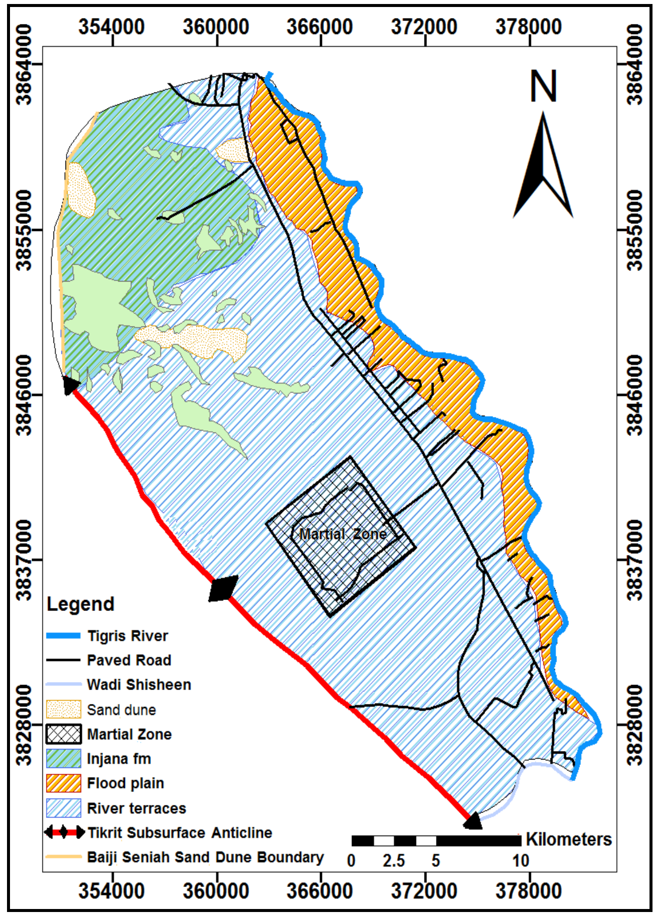


**Figure 2.** Geological map of the study area

## 3. Materials and Methods

### *3.1 Hydro-Geophysical Data*

The hydro-geoelectric characteristics produced from 40 well-distributed VES stations to cover the majority of the research region are used to determine the best groundwater well placements, as illustrated in Figure 3. The bulk resistivity and thickness of the aquifer are the main geoelectrical characteristics acquired from the VES analysis (Figure 4). The aquifer's hydro-geoelectric properties include depth, resistivity, thickness, Longitudinal conductance, and Transmissivity. These characteristics are the most influential since they reflect the amount and quality of possible groundwater that will be collected from this location. The data set utilized in this investigation is shown in Table 1. Longitudinal conductance (S) can defined as the sum of all the thickness/resistivity ratios of n − 1 layers which overlie a semi-infinite substratum of resistivity. It can be represented by the following equation:

$$S = \frac{h}{\rho} \quad \text{.......................................................} \quad (1)$$

Where ***S*** is the longitudinal conductance, measured in (Ω-1), ***h*** is the thickness of the layer in meters, and ***ρ*** is the resistivity of the layer in (Ω.m) (Kirsch & Yaramanci, 2009).

Transmissivity is defined as the ability of the aquifer to pass water through a vertical section of the aquifer with an area of one square unit area at the prevailing temperature (Walton, 1970). The transmissivity coefficient depends on the value of the hydraulic conductivity of the sediments that make up the aquifer and on the thickness of the layer saturated with groundwater, as in the following equation:

$$\mathbf{T = K \, . \, b} \quad \ldots\ldots\ldots\ldots\ldots\ldots \; (2)$$

Where $T$ is the transmissivity in ($m^2$/day), $K$ is the hydraulic conductivity in (m/day), and $b$ is thickness of the layer saturated with groundwater in in meters.

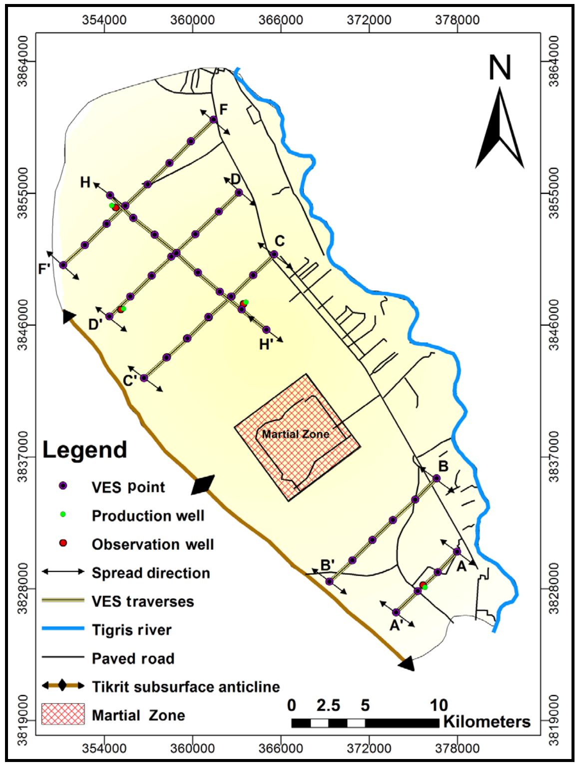


**Figure 3.** A map depicting the VES locations and the geoelectric traverse direction

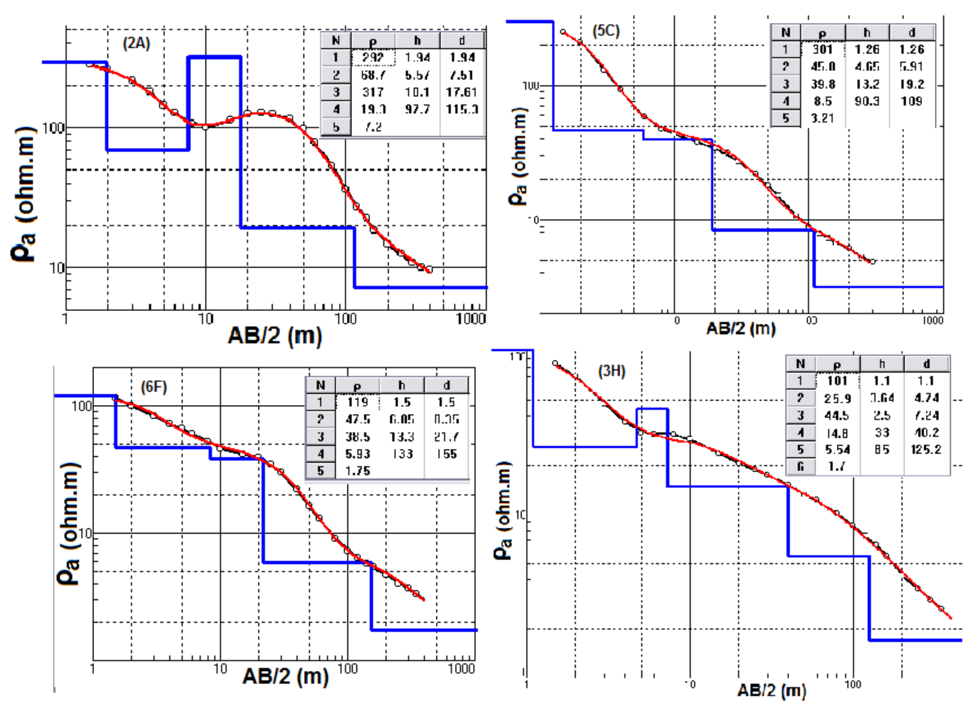


**Figure 4.** VES quantitative interpretations from VES data

**Table 1.** The aquifer's hydrogeophysical data.

| # | VES Name | Long. (UTM) | Lat. (UTM) | Depth (m) | Aquifer resistivity (Ω m) | Aquifer thickness (m) | Longitudinal conductance ($\Omega^{-1}$) | Transmissivity ($m^2$/day) |
|---|---|---|---|---|---|---|---|---|
| **1** | 1A | 378000 | 3830463 | 24.5 | 33.8 | 93.61 | 2.770 | 999.022 |
| **2** | 2A | 376692 | 3829070 | 17.61 | 19.3 | 97.7 | 5.062 | 773.037 |
| **3** | 3A | 375368 | 3827790 | 13.74 | 25.9 | 93.7 | 3.618 | 883.209 |
| **4** | 4A | 373858 | 3826330 | 17.44 | 52.9 | 89.8 | 1.698 | 1176.455 |
| **5** | 1B | 376644 | 3835478 | 32.71 | 65.2 | 91.8 | 1.408 | 1277.348 |
| **6** | 2B | 375159 | 3834038 | 28.91 | 30.2 | 91.7 | 3.036 | 940.851 |
| **7** | 3B | 373696 | 3832620 | 27.76 | 14.7 | 95.4 | 6.490 | 643.766 |
| **8** | 4B | 372256 | 3831274 | 32.04 | 14.7 | 100 | 6.803 | 664.327 |
| **9** | 5B | 370909 | 3829880 | 35.62 | 36.7 | 91.4 | 2.490 | 1024.530 |
| **10** | 6B | 369330 | 3828440 | 30.23 | 41.1 | 94.2 | 2.292 | 1087.143 |
| **11** | 1C | 365568 | 3850779 | 28 | 9.14 | 79.5 | 8.698 | 356.693 |
| **12** | 2C | 364151 | 3849363 | 30 | 12.6 | 75.55 | 5.996 | 474.609 |
| **13** | 3C | 362643 | 3847900 | 27 | 20.5 | 76.66 | 3.740 | 693.487 |
| **14** | 4C | 361110 | 3846507 | 26 | 11.5 | 79.44 | 6.908 | 456.646 |
| **15** | 5C | 359670 | 3845020 | 19 | 8.5 | 90.3 | 10.635 | 381.096 |
| **16** | 6C | 358277 | 3843766 | 21 | 10.7 | 84.57 | 7.904 | 452.487 |
| **17** | 7C | 356744 | 3842327 | 26 | 9.14 | 79.53 | 8.701 | 356.857 |
| **18** | 1D | 363153 | 3855006 | 35 | 6.73 | 68.63 | 10.198 | 158.860 |
| **19** | 2D | 361807 | 3853705 | 33 | 13.8 | 79.75 | 5.779 | 537.950 |
| **20** | 3D | 360227 | 3852173 | 27 | 8.58 | 87 | 10.140 | 368.448 |
| **21** | 4D | 358602 | 3850640 | 24 | 10.2 | 80 | 7.843 | 407.338 |
| **22** | 5D | 357255 | 3849340 | 24 | 7.55 | 81.54 | 10.800 | 284.314 |
| **23** | 6D | 355815 | 3847900 | 23 | 10.7 | 61 | 5.701 | 309.845 |
| **24** | 7D | 354376 | 3846553 | 24 | 8.37 | 70 | 8.363 | 262.705 |
| **25** | 1F | 361435 | 3859975 | 23.4 | 8.81 | 79.23 | 8.993 | 339.152 |
| **26** | 2F | 359902 | 3858489 | 30.4 | 6.12 | 117 | 19.118 | 350.283 |
| **27** | 3F | 358463 | 3857003 | 19.4 | 9.58 | 124.23 | 12.968 | 572.113 |
| **28** | 4F | 356930 | 3855563 | 26 | 6.67 | 147 | 22.039 | 487.516 |
| **29** | 5F | 355467 | 3854123 | 22 | 5.05 | 137.4 | 27.208 | 336.551 |
| **30** | 6F | 354143 | 3852869 | 22 | 5.93 | 133 | 22.369 | 391.325 |
| **31** | 7F | 352704 | 3851429 | 30.6 | 5.05 | 96.3 | 19.069 | 181.368 |
| **32** | 8F | 351218 | 3850036 | 29 | 14 | 99 | 7.071 | 638.637 |
| **33** | 1H | 354422 | 3854820 | 22 | 14.1 | 129 | 9.149 | 757.311 |
| **34** | 2H | 356001 | 3853287 | 24.3 | 6.27 | 107 | 17.065 | 321.846 |
| **35** | 3H | 357441 | 3852126 | 40.2 | 5.54 | 85 | 15.343 | 167.305 |
| **36** | 4H | 358927 | 3850872 | 35.1 | 10.46 | 50.8 | 4.857 | 220.051 |
| **37** | 5H | 360413 | 3849525 | 24 | 9.47 | 59.3 | 6.262 | 244.188 |
| **38** | 6H | 361899 | 3848225 | 27 | 10.2 | 68.53 | 6.719 | 339.771 |
| **39** | 7H | 363339 | 3847017 | 25 | 7.6 | 62.8 | 8.263 | 173.180 |
| **40** | 8H | 365011 | 3845624 | 39 | 7.23 | 72.6 | 10.041 | 214.702 |

### *3.2 Criteria Layers Standardization*

The initial stage in merging criterion layers is to unify the layers into a single scale. The fuzzy liner membership technique was employed to standardize all classes in this investigation. This stage transforms the layer into such a scale with a value ranging from 0 to 1, with 1 denoting a suitable zone and 0 denoting an unsuitable region. According to Benz et al. (2004), the fuzzy linear equation is as follows:

$$\mu(X) = \begin{cases} 0 & \text{if } x < min \\ 1 & \text{if } x > max \\ \frac{(x - min)}{(max - min)} & \text{otherwise} \end{cases} \quad \ldots\ldots\ldots\ldots\ldots (3)$$

### *3.3 Fuzzy Overlay*

This stage uses overlay processing to aggregate all layers of the standards to predict the best site for drilling groundwater wells.

GIS methodologies were used to generate the suitability study, which was based on numerous criterion layers. All criterion layers were combined in ArcGIS 10.8 to create a map with a fuzzy overlay that depicted the optimal location for drilling new groundwater wells. A flowchart of the appropriateness model is shown in Figure 5. In a multi-criteria superposition analysis, the fuzzy overlay tool may be used to examine the chance of a phenomena belonging to several categories happening. The possible approaches for integrating data based on group theory analysis are listed in the overlay type. Five approaches are available in ArcGIS (fuzzy gamma, fuzzy product, fuzzy and, fuzzy or, and fuzzy sum). Fuzzy gamma is employed in this research as the output of fuzzy sum and fuzzy product that are both increased to the intensity of gamma operator. According to Baidya et al. (2014), the generic function is as follows:

$$\mu\,\text{combination} = \begin{cases} \prod_{i=1}^{n} \mu_i & \text{(For Fuzzy algebraic product)} \\ \prod_{i=1}^{n} (\mu_i - 1) & \text{(For Fuzzy algebraic sum)} \\ (\text{Fuzzy algebraic Sum})^{\lambda} \times (\text{Fuzzy algebraic product})^{(1-\lambda)} & \text{(For Fuzzy gamma)} \end{cases} \quad ..(4)$$

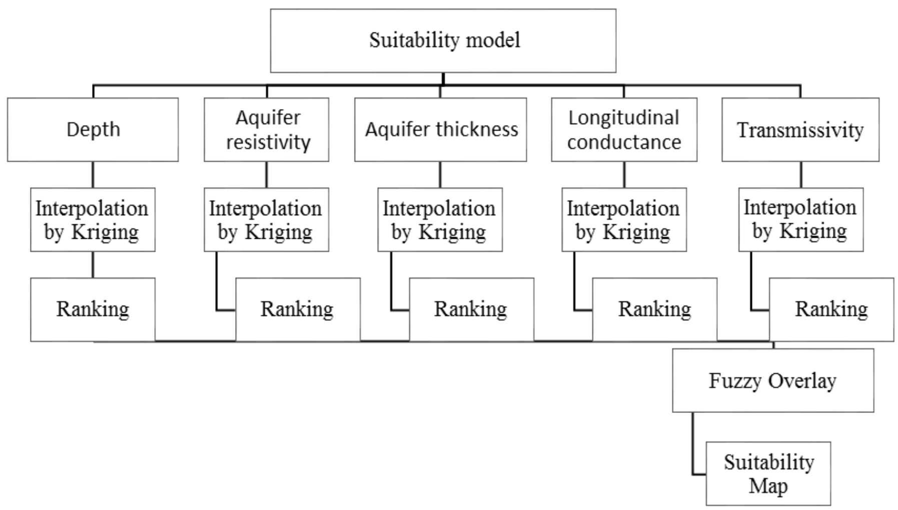


**Figure 5.** Flowchart of the Suitability model

## 4. Results and Discussion

### *4.1 Interpolation of the Criteria Layers*

The criterion layers were used to evaluate the GIS and hydro-geoelectric factor combination's results. Using the GIS method of aggregating intersections (i.e. the values of depth, resistivity, thickness, longitudinal conductance, transmissivity). As indicated in Figure 5, Kriging interpolation method was applied to interpolate layers of hydro-geoelectric parameters (Figure 6). Depth values range from 23 to 32 m, resistivity values range between 5-70 Ω m, the thickness ranges from 52 to 160 m, and longitudinal conduction values ranging between 3 to 20 $\Omega^{-1}$, while conductivity values vary from 160 to 1500 $m^2$/day.

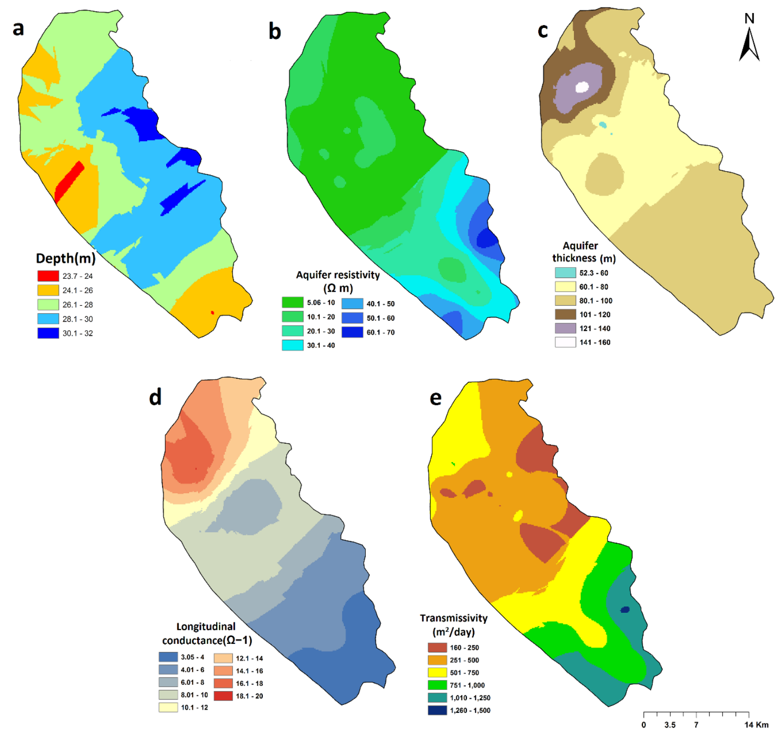


**Figure 6.** Interpolation of the criteria layers (a-Depth, b-Resistivity, c-Thickness, d-Longitudinal conductance, e-Transmissivity) using Kriging method.

### *4.2 Site Suitability Model*

The initial step in developing a site relevance model was to harmonize all levels of the criterion. The linear fuzzy membership (FLM) method is used for this stage. The fuzzy linear membership of the five criterion layers employed in this investigation is shown in Figure 7. Finally, using a fuzzy gamma overlay, these factors are integrated to create a suitability map, as illustrated in Figure 8. The research region was divided into four groups by the findings map: excluded, low suitability, moderate suitability, and high suitability. Table 2 displays the total area as well as the proportion of each category that has been determined and explained. The research was necessary because the northwest section of the study region is considered to be ideal for digging additional groundwater wells that meet the specified specifications.

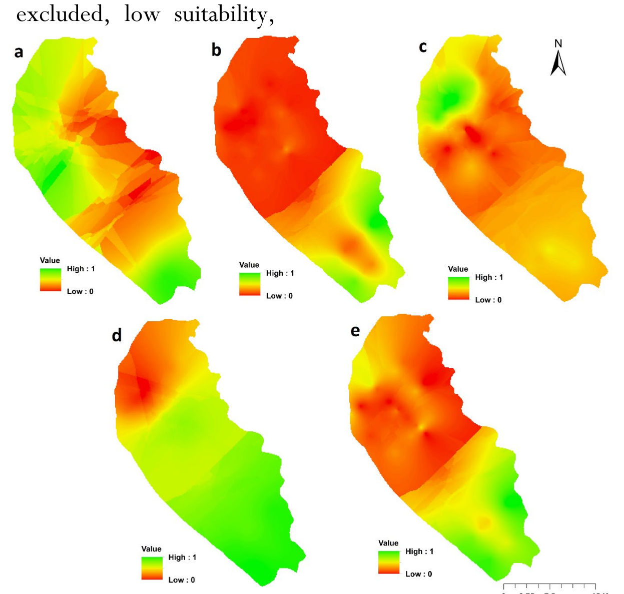


**Figure 7.** Liner membership of the criteria layers (a-Depth, b-Resistivity, c-Thickness, d-Longitudinal conductance, e-Transmissivity) using fuzzy method.

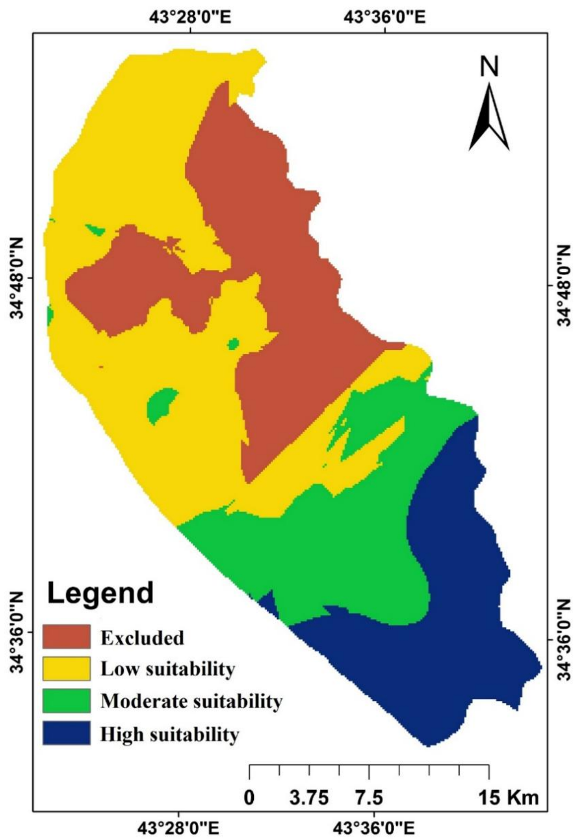


**Figure 8.** Site suitability map using fuzzy gamma algorithm

**Table 2.** The total area and percentage for each suitability category

| Category | Area (km2) | Percentage |
|---|---|---|
| Excluded | 172.5365 | 24.59677 |
| Low suitability | 269.7671 | 38.45794 |
| Moderate suitability | 131.891 | 18.80235 |
| High suitability | 127.2654 | 18.14293 |
| Total | 701.46 | 100 |

## 5. Conclusions

This study demonstrated the capabilities of the multi-criteria evaluation technique via GIS in analyzing the suitability for selecting suitable sites for drilling new groundwater wells in the southeastern and northwestern part of the study area. Groundwater appropriateness study immediately aids the community in alleviating the water situation. Based on hydrogeoelectric data, a multi-criteria evaluation approach using GIS software and fuzzy logic is utilized to select the best places for digging new groundwater wells. Excluded, low, moderate, and high appropriateness were the four categories used to categorize the research region. According to the study, the southern and southwestern parts of the study region should be ideal for digging additional groundwater wells that meet the recommended specifications. The many governmental agencies engaged in the management of water resources in Salah al-Din Governorate should implement this strategy. Furthermore, further research in this area is needed to establish a scientific foundation for an effective water management system in Iraq.

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# The Evaluation on Thermal Performance of *Rumah Negeri Sembilan Berserambi Dua dan Beranjung*

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**ABSTRACT**

Traditional Malay house, a passive design architecture, is believed to have more effective thermal performance than modern residential houses through climatic design strategies. Unfortunately, the Malay house has experienced numerous changes and is confronted with constant dangers due to present-day science and innovation. Thus, this study aimed at evaluating the thermal performance of *rumah* Negeri Sembilan *berserambi dua* dan *beranjung* for sustainable practice in the tropical environment. The method used was fieldwork: observation and thermal measurement. Comparing the suggested comfort level by ASHRAE 55 and ICOP, 20% percent of the total data is falls within the thermal comfort range suggested. However, the house is considered in comfort environment between 25-27ºC, which is only in the early morning. As for the wind flow, each house division recorded different readings. However, it was still within the comfort level range, i.e., between 0.12-1.25m/s, while the RH level was 50-60%. Therefore, the primary findings elaborate that the Malay house construction has five factors that directly influence the house's thermal performance. These include floor areas, openings, floor and roof heights, materials, open compound areas, and building setting. This study aspires to provide useful insights regarding the effectiveness of practices in the climatic design strategies of a traditional Malay house. Thus, its contribute to the scientific discussions on sustainable practices in modern residential design which aligned with the Twelfth Malaysia Plan (RMK12) Theme 3.

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## 1. Introduction

Passive design strategies take advantage of natural energy opportunities, to maintain thermal comfort in a building. In order to achieve and maintain thermal comfort, climatic design strategies are practiced. The strategies are about the appropriate building orientation and design, the properties of building materials, the local climate, and landscaping (Gulpınar Sekban and Düzgüneş, 2021; Jamaludin et al., 2021; Marro, 2018; Altan et al., 2016; Misni, 2015). These design strategies aim to produce an effective indoor thermal performance by capitalizing on prevailing winds and promoting indoor natural cross ventilation. Besides, they are also intended to avoid direct solar radiation in the interior spaces while ensuring natural daylight in the building. The strategies of this design are substantially practiced in vernacular architecture (Shaeri et al., 2018; Rapoport, 1969).

Understanding the climatic adaptations of the vernacular architecture requires understanding the climatic and environmental conditions of the houses's location. As a tropical country, Malaysia's climate can be classified as hot and humid. Its high temperature and humidity characterize it. Air temperature averages should be between 28 and 32°C with small annual and diurnal ranges. According to MetMalaysia (2021), humidity is high throughout the year, with an average of about 75% or more. Consequently, direct solar radiation is filtered with heavy clouds covering the high-water vapor content in the air. The winds are generally of low-variable speed, but strong winds can occur with the rains. Rainfall is also high throughout the year averaging from 2500 to 3000mm annually. To achieve optimal climatic control, the traditional houses are designed appropriately to suit specifically the vagaries of the tropical climate of Malaysia. They are appreciably suited to the local climate.

### *1.1 Climatic Design Strategy of Malay House*

In Malaysia, these design strategies were developed and applied in traditional houses such as traditional Malay houses (TMH). According to Johari and Said (2021), Malay houses are among the best traditional houses that practice climatic design strategies. TMH is believed to have the right harmony with the environment by being responsive to the surrounding physical environment (Yaa'cob et al., 2021; Toe and Kubota, 2014; Toe and Kubota, 2013; Huang and Liu, 2010). It is known for its distinctive characteristics of the climatic design that give a positive response to the thermal condition.

The main element of its thermal qualities is raising the house floors on posts above the ground using low thermal conductivity materials, such as timber. Secondly, it has plentiful windows and ventilation lattices while possessing minimal partitions in open interior spaces to provide cross ventilation. Another element is the high or steeply sloping roof with ventilated *tebar layar* and *lubang angin* that promote cross ventilation. In contrast, the low wall of the house is to control direct solar radiation. Lastly, the houses are randomly arranged in the village area, strategically planting vegetation to allow wind paths (Kumar and Sharma, 2021; Misni, 2016; Kubota and Toe, 2012).

Research on the evaluation of the thermal performance of TMH in Malaysia has been widely done. Full-lenght operable windows allow maximum air from outside into the interior spaces, producing indoor cross-ventilation but poor performance in the stack effect (Hassan and Ramli, 2010). Meanwhile, Mohd Nawayai et al. (2020), Roslan et al. (2015), Abd Wahab and Ismail (2014) have proven that houses being raised on stilts with floor joist and having *lubang angin* as well as steeply sloping roofs with ventilated gable ends do contribute to encouraging air movement into the buildings. Besides, shady trees without bushy shrubs in huge lawn areas give less obstruction in allowing maximal cross-air ventilation and reducing direct solar radiation (Misni, 2016; Misni, 2015; Abd Wahab and Ismail, 2014; Toe and Kubota, 2013). Hence, these have proved that the Malay house is an intelligent building design as it depends entirely on natural resources and is built responding to local climatic conditions' needs.

### *1.2 Neglection of Traditional Construction Technology*

Unfortunately, the Malay house is experiencing numerous changes and is confronted with constant dangers to its proceeded presence. Policymakers, analysts, and experts' inclination toward present-day science and innovation has led to the disregard and decay of its technologies and cultural forms. In addition, proper local building materials and design principles of the TMH forms are being supplanted by advanced impacts (Husen and Mohamed, 2021; Lim, 2010). As a result, the intelligent traditional construction techniques of the Malay house are being brought down and deserted.

Subsequently, house forms ought to alter to fit the changing needs of the users. Progressive changes within the Malay house forms are troublesome and improper since such changes are frequently forced from external sources and are missed by the local communities. Consequently, these changes are often insignificant and neglect local and socio-economic, social, and environmental conditions (Manurung et al., 2022; Lim, 2010). Sahabuddin (2016) stressed that when observing Malaysia's current housing project scenario, practically no housing concept can match traditional Malay houses' 'ancient science' concept.

### *1.3 Thermal Performance Evaluation*

Therefore, this study highlighted research about evaluating the thermal performance of *rumah Negeri Sembilan berserambi dua dan beranjung* for sustainable practice in the tropical environment. According to previous studies, there is a lack of experimental studies done on thermal performance evaluation that engages the TMH which have curved roof structure and elongated floor plan. Roof with height angle design would give a positive effect as the incident solar radiation angle reaches zero degrees, reducing the solar radiation's penetration to the house (Ramly and Hussain, 2006). Furthermore, a shallow floor plan is more efficient because it facilitates more airflow inside the structure, practising the cross-ventilation technique (Yüksek and Karadayi, 2017). Correspondingly, previous studies' inference shows that most experimental studies on thermal performance have been keen on the basic design of *bumbung panjang*, *bumbung limas*, and Malay houses without the open passageway (Johari and Said, 2021; Saad et al., 2019; Toe and Kubota, 2013; Hassan and Ramli, 2010).

In this study context, evaluating is defined by using quantitative and qualitative techniques that can be used to assess the indoor thermal performance of the house. Moreover, the thermal performance of a building refers to the process of modeling the energy transfers between a building and the surroundings (Rathore et al., 2022; Nordin and Misni, 2017; Joseph et al., 2015; Misni, 2015). This study aspires to provide helpful insight regarding the effectiveness of practices in the climatic design strategies of a TMH. The findings will contribute to the scientific discussion on this subject towards a sustainable approach to modern residential design and the technology used. Besides, it is also aligned with the Twelfth Malaysia Plan (RMK12) Theme 3, where Malaysia aims to be a carbon-neutral country by advancing green growth and enhancing energy sustainability as early as 2050.

## 2. Methodology

In this study, two phases of the fieldwork were used. The first phase is the pre-survey case study, and the next phase is the data collection, as illustrated in Figure 1.

## *2.1 Phase 1*

A pre-survey case study was applied to identify the potential case study. This process is required to obtain the case study material that fulfilled the criteria set. A purposive sampling method was applied to discover, understand, and gain insights at this research stage.

### 2.1.1 Type of House

*Bumbung panjang* (long roof) is Malaysia's most typical house form and has been chosen as the case study's house form. *Rumah bumbung panjang* in Negeri Sembilan have curved roof structure and elongated floor plan. Abdul Wahab and Bahauddin (2019), and Ismail et al. (2016) mentioned that the roof structure design is differ from other states due to evolve of a cultural migration movement by the people of Minangkabau. There are several typologies of the house and *rumah Negeri Sembilan berserambi dua dan beranjung* (RBDB) was chosen as the case study. This typology has curved roof structure slightly at the left and right, has *bumbung cerun bertingkat* (double-slope roof) between the roof of the *rumah ibu* and *serambi,* and the *tebar layar* (gable ends) at both ends of the roof (Ismail et al., 2016; Yaakub, 1996). Commonly, *rumah Negeri Sembilan* with *anjung* are for the houses of traditional chiefs and dignitaries (Ismail et al., 2014), others have different sizes and architectural styles and this can be clearly seen in the *serambi* (Ismail et al., 2017).

Furthermore, to identify the appropriate potential of case study, there are five justifications of house criterias were adopted as a guideline (Table 1); age of the house, house unit, authenticity, compound distribution, and cooling equipment. The criterias were obtained based on the analytical review of previous studies and documentation (Abdul Wahab and Bahauddin, 2019; Ismail et al., 2017; Ismail et al., 2016; Sahabuddin and Gonzalez-Longo, 2015; Kubota and Toe, 2012; Feilden, 2003).

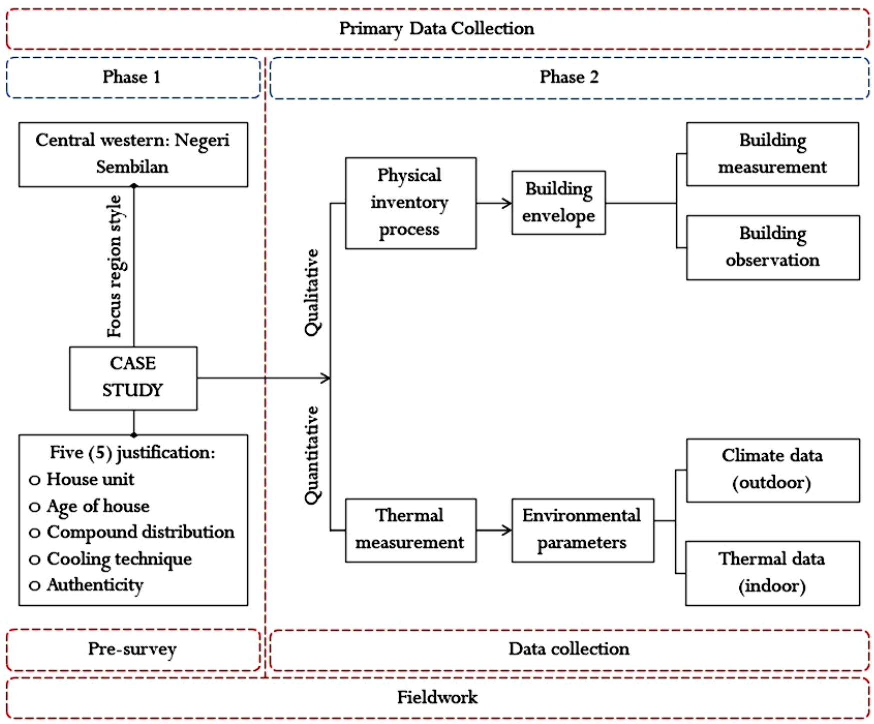



**Figure 1** Fieldwork flowchart

**Table 1** Case Study House Selection Criteria

| Items | Authentic elements |
|---|---|
| House unit | Single-family house of traditional Malay house |
| Age of house | Approximately a 100 years old |
| Compound distribution | Malay house compound (front, sides, and back yard) |
| Building cooling control | Natural ventilation |
| Authenticity | Physical requirement elements (minor modification):<br>○ Use local low thermal capacity materials of building envelopes (wall/floor/roof) |

| | |
|---|---|
| | ○ Elevated from the ground (built on stilt)<br>○ The large opening of the window and other openings<br>○ Original landscaping/edible/native plants in the surrounding compound<br>○ Strategic orientation of the house |

### 2.1.2 Study Location

The selected study location for the RBDB typology was in Kuala Pilah, Negeri Sembilan. Kuala Pilah is located 37.9km to the east of Seremban. The study location was identified by reviewing previous studies for instance, Abidin et al. (2018), Abdul Latif and Kosman (2017), Sulaiman (2016), Ismail et al. (2016), Ismail et al. (2014), Chen et al. (2008) as well as the database from Center for the Study of the Built Environment in the Malay World (KALAM). Another relevance of selecting this specific location was due to the opportunity to access the house's thermal performance. In addition, the house also fulfills the essential requirement stated in Table 1.

## *2.2 Phase 2*

A fieldwork study was carried out through observation and thermal measurements of the selected case study.

### 2.2.1 Data Collection

The primary data collection in this study used mixed methods; qualitative and quantitative. The first is qualitative via on-site physical observation and measurement which is called as on-site physical inventory process. This process requires collecting information regarding the following details: measurement of the house and compound with the layout respectively, physical architectural elements, building materials used, and mechanical ventilation system utilized in the house. The second was quantitative, thermal performance measurement. The data collection was conducted in August 2021 as this is the month when the most stable rainfall at an average of 150 to 250mm which expected in Negeri Sembilan, according to the Meteorology Department of Malaysia. Thus, the thermal data would be calm, and the sky is clear with medium cloud cover.

The thermal data collection was conducted in the interior spaces and exterior areas of the house. The indoor data acquisition point are about 1.1m above the floor level (ASHRAE, 2017) and 1.2m distance from any wall (CLEAR, 2019). In contrast, the outdoor area measurements are not less than a one-meter distance from the wall of the house and about 1.5m above the ground levels (Collow, 2020). There were 12 selected data acquisition points both indoor and outdoor (Figure 3). The data recorded were within 12 hours, from 07.00 until 19.30, with 30 minutes intervals over three days. No measurement was carried out at nighttime due to the owner's privacy.

In conjunction, other rationale the measurement taken only in daytime because it is the peak time where heat exists due to the presence of the sun. Therefore, it is reasonable in evaluating the influence of house design on the degree of regulation of indoor thermal performance. The data were only taken during the overcast sky (partly cloudy) condition, which is a typical type of sky condition in the tropical climate of Malaysia (MetMalaysia, 2021). No survey was conducted in rainy and clear sky condition. It is because the scope of this study was only to evaluate the thermal performance during the ordinary climate of Malaysia.

### 2.2.2 Environmental parameter and the comfort zone

Three specific environmental parameters were taken to measure thermal performance: air temperature, relative humidity (RH), and wind speed. The measurable scale for temperature is Celsius (°C), RH in percentage (%), and wind speed in meters per second (m/s) (ASHRAE, 2017). All parameters were measured using Delta OHM HD32.3 Data logger. The validation of climate data, including hourly temperature, relative humidity, wind direction and speed, and solar radiation, was obtained from the nearest meteorology station, Kuala Pilah Station and Hospital Seremban.

In order to identify and verify thermal performance and comfort zone of the house, the comfort zone recommended by ASHRAE Standard 55 (ASHRAE, 2017) and the Industry Code of Practice (ICOP) on Indoor Air Quality (IAQ) 2010 in the psychrometric chart (Figure 2) is used as a reference. Whereas the Malaysian Standard Energy Efficiency and Use of Renewable Energy (MS 2680:2017) (Table 2) is the measurable scale for the wind speed.

Sookchaiya et al. (2010) stated that the comfort zone by ASHRAE 55 in the psychrometric chart is the standard used worldwide. However, it can have a little different value because the climate type in any country worldwide varies with their comfort levels. Thus, their comfort zone has not been defined though. Based on the standard illustration in Figure 2, the comfort zone recommended by ASHRAE 55 is represented in the blue zone. The indoor temperature at the comfort level was supposed to be between 19 and 27ºC. Moreover, ASHRAE 55 suggests that the RH level should be between 30-80%.

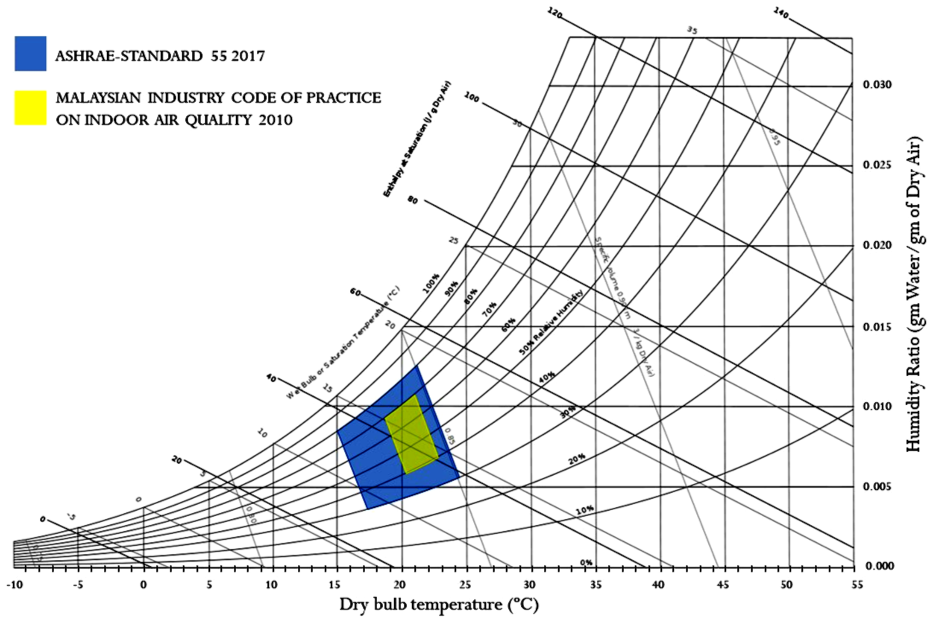



**Figure 2** The thermal comfort zone in the standard psychrometric chart
(Modified from ASHRAE standard 55 and Malaysian Industry Code of Practice (ICOP) on Indoor Air Quality (IAQ) 2010)

**Table 2** The Measurement Scale for Wind Speed based on the MS 2680:2017

| Scale | Unit (m/s) | Description | Occupant sensation |
|---|---|---|---|
| 1 | ≤ 0.25 | ○ Smoke (from a cigarette) indicates movement | ○ Unnoticed, except at low air temperatures |
| 2 | 0.25 - 0.5 | ○ Flame from a candle flicker | ○ Feels fresh at comfortable temperatures but draughty at cool temperatures |
| 3 | 0.5 - 1.0 | ○ Loose papers may be moved. Equivalent to ○ walking speed | ○ Generally pleasant when comfortable or warm but causing constant awareness of air movement. |
| 4 | 1.0 - 1.5 | ○ Too fast for deskwork with loose papers | ○ Acceptable in warm conditions but can be from slightly to uncomfortably draughty |
| 5 | > 1.5 | ○ Equivalent to a fast-walking speed | ○ Acceptable only in very hot and humid conditions when no other relief is available. Requires corrective measures if comfort and productivity are to be maintained |

However, the Industry Code of Practice (ICOP) on Indoor Air Quality (IAQ) 2010 (yellow zone) proposed that indoor thermal comfort in Malaysia is slightly different from the ASHRAE 55. The recommended indoor thermal comfort should be at 23-26ºC, while the RH is between 40-70%. As for the wind speed, ASHRAE considered efficient indoor wind speed performance is between 0.1 and 0.8m/s. According to MS 2680:2017 (Table 2), the wind speed scale recommended by ASHRAE 55 is 1 to 3. Compared to the ICOP on Indoor Air Quality (IAQ) 2010, the suggested appropriate indoor wind speed is 0.15-0.50m/s on scales 1 and 2.

Nevertheless, the Beaufort Scale, a system for estimating wind strengths advises that the best wind speed performance level should be 1.6-5.4m/s. If the wind speed measurement is below 1.5m/s, the interior condition might be less convenient due to stagnant air and low wind flow to evacuate warm air to the outdoor. Compared to ASHARE 55 and ICOP on Indoor Air Quality (IAQ) 2010, it is shown that the Beaufort Scale prefers more significant air movement to provide a pleasant indoor environment for the occupant.

## 3. Results and Discussions

### *3.1 Case study*

A RBDB located at Kampung Cheriau, Senaling, Kuala Pilah, with 2°41'39.5"N Latitude, 102°13'41.9" E Longitude, and an elevation around 114m above sea level was chosen as the case study. The house owner is Mr. Razali A. Kadir, and it was inherited from his late grandfather. Four occupants are living in the house. The age of the house is around 153 years with a total built-up area of 152.62m$^2$, and the outdoor lawn compound area is 604.71m$^2$.

The house has possess the criterias as in Table 1. The pedestal fans as mechanical ventilation equipment were only used when there are feasts or events. Figure 3 illustrates the orientation of the house and data acquisition point at indoor outdoor area. The front of the house is facing southeast, while the main entrance is oriented to face northeast. In addition, the bedroom is in the southwest direction, and the kitchen is facing northwest. Whereas the main direction of qibla is 293° 30'.

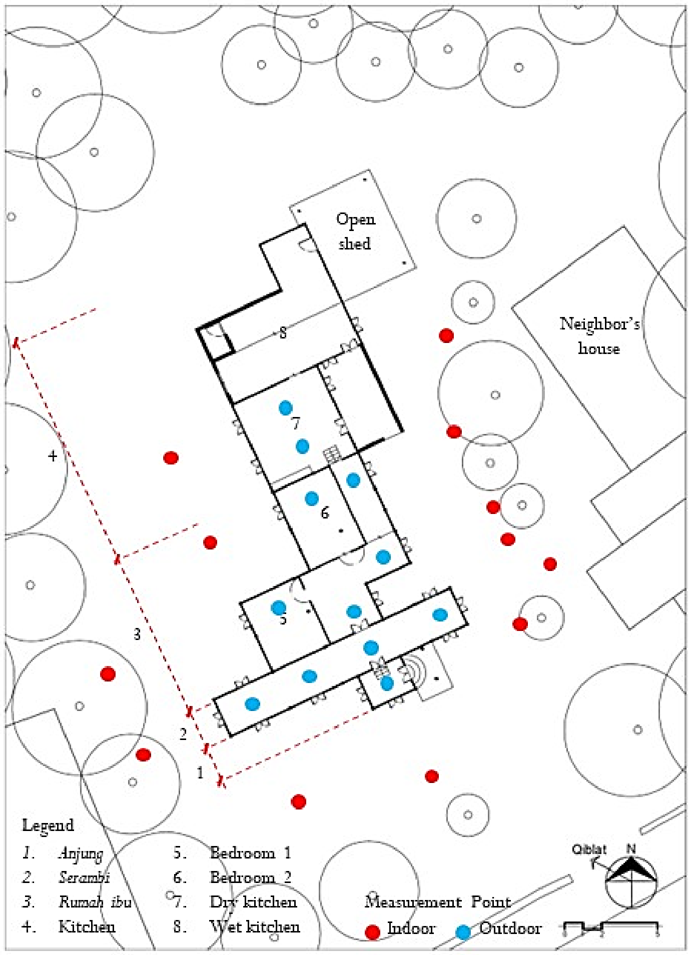
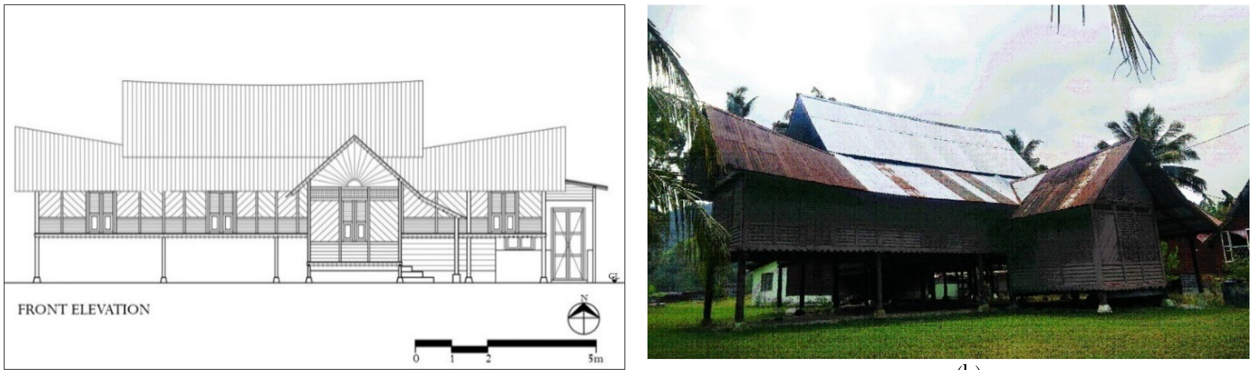



**Figure 3** The house's spatial division and the location of measurement points inside the house and outdoor area

## 3.2 *Physical Inventory Data*

The roof design has curved roof structure slightly at the left and right, and *tebar layar* at both ends, as shown in Figure 4a. The house was designed with *bumbung cerun bertingkat* between the roof of the *rumah ibu* and *serambi*. This indicates that the house has ample roof space with the highest roof pitch at *rumah ibu* which reaches about 5.6m. In addition, the roof has ventilated gable end features. The original roof material has been replace to zinc sheet (Figure 4b) and was designed without a ceiling. The case study has four spatial divisions: *anjung*, *serambi*, *rumah ibu,* and kitchen. The house was built on stilts which is only at the front part of the house. It has a timber structure elevated about 1.2m (*serambi*) *and 1.*35 (*rumah ibu*) above the ground. Moreover, the *anjung* is elevated above the ground by about 0.5m. While the rear parts of the house were built using a brick-and-timber structure directly on the ground; kitchen and toilet. The house has undergone some modifications and extensions of space. The wet kitchen and open shed are the areas that have been extended from the actual space.

*Rumah ibu* is the largest area with 53.9m$^2$ (compared to the other front part) followed by *serambi*, 29.3m$^2$. In comparison, *anjung* is the compact among the spatial division, which is 4.6m$^2$. The house was constructed using timber material. The floor and roof joist, as well as gable ends with ventilation lattice are examples of passive ventilation devices in house construction (Figures 5). Besides, the house has plenty of full-lenght operable windows at body level. Moreover, the house was also fabricated with ventilated *kepala tingkap pagar musang* and *lubang angin*. Besides, the windows came with wooden louvers paneling. As for the floor finishes, the house uses a rubber mat in Bedroom 1, dry and wet kitchen, while the other spaces are not covered with any finishes. Thus, indirectly, it has many passive ventilation devices that convey natural airflow into the house.




(a) (b)

**Figure 4** The front elevation (a), and the roofing material which is using zinc

(a) (b)

**Figure 5** Plenty of full-length operable windows at the body level, ventilated *kepala tangkap, pagar musang* and *lubang angin* (a), and the ventilated gables end and f full-length wooden panel operable windows with louvers paneling (b)

### *3.3 Thermal data*

The average thermal (indoor and outdoor) were recorded according to the spatial divisions; *anjung*, *serambi*, *rumah ibu,* dry kitchen and outdoor area. The instrument's setup and the house's thermal data measurements are presented in Figure 6 and Figure 7.

Based on the overall measurement, most of the time, the indoor air temperature ranged between 30.2 and 35.7ºC which were not under comfort level. The house was only under a comfort level between 07.00 and 09.00 hours which is refer to the psychrometric chart. The temperature ascended from early morning until late noon, with the solar radiation pattern recorded at 2.75 MJ/m$^{-2}$ at 14.30 hours. This situation happened due to the material used in upper part (roof), which is zinc. The roof is exposed to heat caused by high solar radiation and high emissivity levels. The roof accumulates heat, cause the indoor air temperature arised. The RH reading was within the comfort level range (73.2-74.8%) between 09.00 and 19.30 hours. While wind speed data recorded were also within the acceptable range which is between 0.12 and 1.25m/s (Scale 1 to 4) and it is acceptable in warm conditions.

*Anjung* recorded the highest indoor temperatures at peak hours (11.30-14.00 hours) than the other spatial divisions. It ranged between 35.3 and 35.5ºC, which was not in a comfortable environment. While, RH level is maintained at the comfort level during the peak hour and the reading was between 52.5 and 57.7%. As for the wind speed reading, it recorded the most wind flow. The reading was between 0.38 and 1.26m/s (Scale of 2 to 4). However, from early morning until early noon, this area measured the lowest temperature. Other than the zinc roofing driving the increases in temperature, compact space along with *anjung* which was not built elevated above the ground same level as the *serambi* were also part of it. As a result, the warm air is trapped due to compact space even though it receives most wind flow because it cannot smoothly circulate to the adjacent space, *serambi*. Wind flow can easily penetrate into the *anjung* because the half-length operable windows with louvers paneling and ventilated *kepala tingkap* were designed facing the wind flow direction (south to east). In addition, there were fewer trees planted in the lawn front yard. Hence, the wind can freely glide into the space without any obstructions.

(a) (b)

**Figure 6** The setup of the instrument (a), and the Delta OHM HD32.3 Data logger (b)

Meanwhile, the indoor air temperature in the *serambi* was slightly lower than *anjung* at noon but still not in comfort level. The range of differences was 0.2ºC, despite that, the wind speed rate was not as high as *anjung*. It has a light air movement. The reading was within the range of 0.13-1.2m/s (scale 1 to 4). Meanwhile, RH level was within comfort level, between 53.1 and 55.21%. Despite of using the same roofing material, this thermal performance ensued as *serambi* has plenty of full-lenght operable windows with louvers paneling, ventilated *kepala tingkap*, *pagar musang* and *tebar layar* at both ends of the roof. Besides, it was built elevated 1.2m above the ground level. The raised floor built higher than the ground can obtained and enabled higher-velocity winds to pass through, added with elongated open plans without any partition across the space, thus providing a cross-ventilation technique. The maximal wall openings outturn in significant air intakes outside the house aided to dispense warm air into the outdoor area. Despite that it resulting to poor stack effect performance. Furthermore, the floor joist, which creates small gaps between the planks, might help to circulate air throughout the space. While the ventilated *tebar layar* and roof joist were also fabricated to perforate the warm air. Other than that, *serambi* is designed with low roof overhang, minimizes the glare from the sun and the amount of direct sunlight entering the house.

Compared to the *rumah ibu*, even though it was constructed as the middle annex of the house, the indoor air temperature was cooler than *anjung,* and *serambi* but still not under comfort level. The measurement at noon ranged between 33.6 and 34.7ºC. The range of differences was between 0.8 and 1.6ºC. However, the wind flow reading was lower than in *anjung,* and *serambi*, between 0.15 and 0.32m/s (scale 1 and 2). As for the RH level, the reading was uniformed. The range of differences was 0.1%. Eventhough the roofing material is zinc, the thermal reading was lower because *rumah ibu* is designed with *bumbung cerun bertingkat* this means it has ample roof space and the highest roof pitch is about 5.6m. Therefore, the space below the roof helps effectively cool the house by stacking the warm air and executing it through the ventilated *tebar layar* and roof joist. As for the low wind flow rate, despite of having the largest area with 53.9m$^2$ among *anjung,* and *serambi, rumah ibu* was not designed as open floor plan. It has few walls to enclose the bedroom 1 and 2. In addition, this spatial division was built with operable windows without louvers paneling, ventilated *kepala tingkap*, and *pagar musang*. This characteristic resulting in degenerate the wind circulation in the space as well as reduce the speed rate.

The kitchen has recorded the lowest air temperature from noon until evening compared to the other spatial divisions. The measurement ranged between 31.9-33.5ºC, but it is still not within the range of comfort level. The kitchen has ample open space compared to other areas with minimal interior partitions. It also has some half-lenght operable windows with ventilated *kepala tingkap.* Hence, these elements assist in circulating the cool air in interior space without any obstacle. Furthermore, it is also can allow easy passage of warm air discharge from the area. Nevertheless, the wind speed measurement was at the lowest rate in contrast to other spatial divisions. The highest reading was 0.32m/s (scale 2), and most of the time, it was at 0.01m/s. Meanwhile, the RH level was under the range of comfort level. The reading ranged from 55.2 to 55.8%.

To deduce, in the evening (17.30-18.30 hours), all the spaces seems to have a contrary reading where there are significant air temperature differences in comparing to outdoor weather data. It shows that the indoor temperature is higher compared to outdoor data. The same thing also applies to the wind speed reading. There are barely reading at indoor area for all the spaces eventhough outdoor wind speed rate within the scale 1 and 2. This proves that wind movement is essential to cool the interior of the house.

### 3.3.1 Comfort zone of the case study

To identify and verify the house's thermal performance and comfort zone, the average lowest and highest air temperature, as well as the RH, are illustrated in the psychrometric chart (Figure 8). The orange zone in the psychrometric chart indicates the case study's thermal performance. Comparing the suggested comfort level by ASHRAE 55 and ICOP to the house's thermal performance, it stipulate that the indoor environment is not at the comfort level most of the time. It is only about 20% percent of the total data is falls within the thermal comfort range suggested by ASHRAE 55 and ICOP. The comfort condition was only can be experienced in the early morning in all spatial divisions.

Therefore, the factors that influence the thermal environment of the house are identified. Replacing original roof material to zinc sheet give the significant influence towards thermal performance where it has generate a warmer indoor environment. In relation to that, it also reducing the effectiveness passive cooling strategy. The zinc sheet has a fast heat conductor, after receiving radiant heat from the sun, the zinc releases the heat into indoor spaces by employing convection and radiation. This has caused the indoor air temperature increase dramatically. Nevertheless, this Malay house still practices several other climate design strategies to regulate the indoor thermal performance.

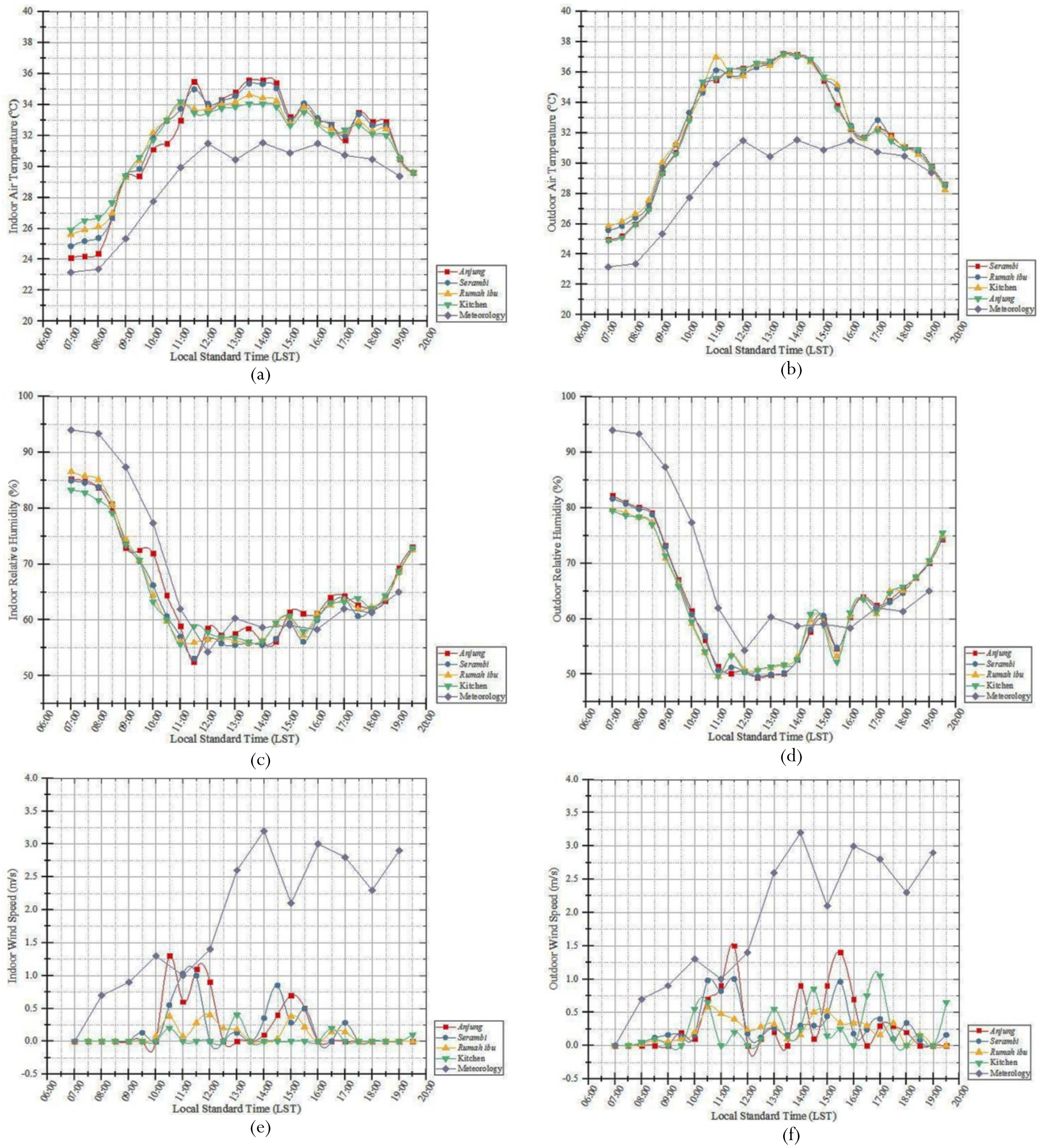



**Figure 7** The house's thermal data measurements

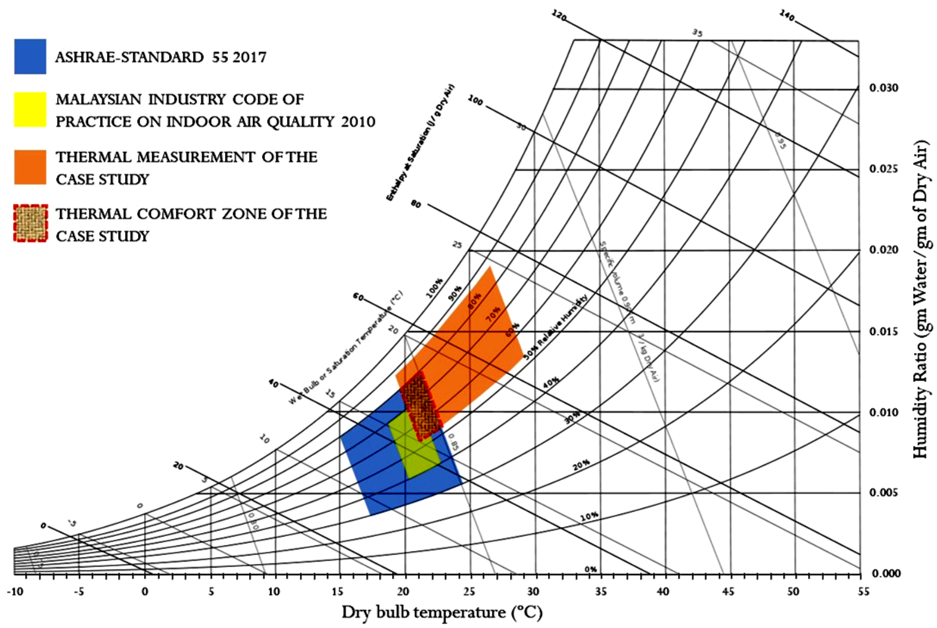



**Figure 8** The comfort zone of the case study

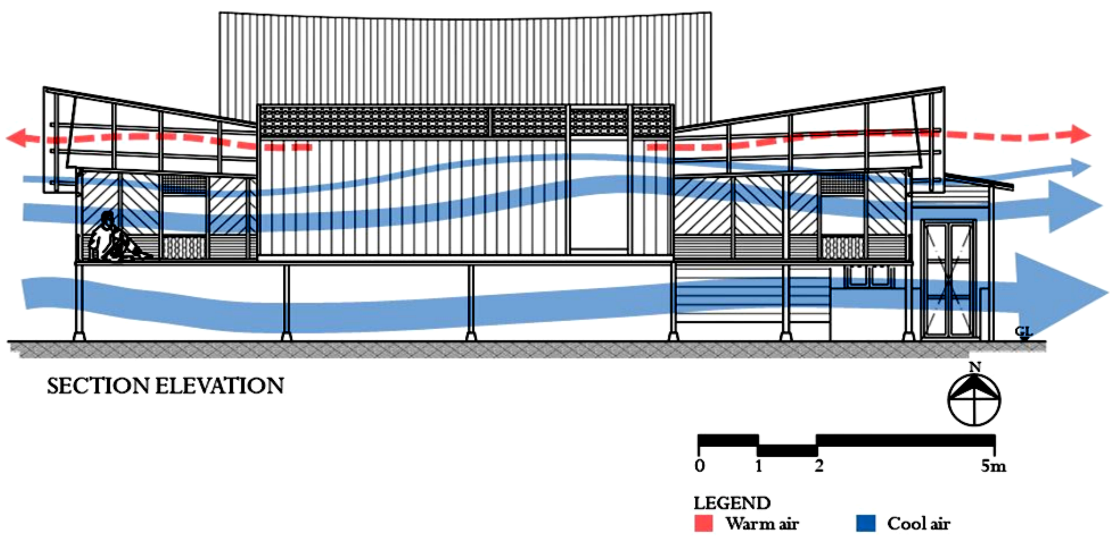



**Figure 9** The passive ventilation through the opening such as windows and *tebar layar*

Elongated open plans without any partition across the space with plenty of operable and large size windows as well as built on stilt were practices, providing cross-ventilation technique (Figure 9). At the same time, *bumbung cerun bertingkat* which has ample roof space, aid the space below the roof to effectively cool the house by practicing the stack effect technique, the warm air were execute through the ventilated *tebar layar* and roof joist. Moreover, in order to encourage wind flow easily penetrate into indoor space, operable windows with louvers paneling, ventilated *kepala tingkap, pagar musang* as well as *lubang angin* were designed strategically facing the wind flow direction. Other than that, there were fewer trees planted in the yard. The plant is in strategic placements around the house's compound area, thus the wind can freely into the space without any obstructions.

## 4. Conclusion

This study has demonstrated the essential strategies that existed in TMH, technically. The passive and climatic design strategies in TMH have a lot to offer to develop building construction, especially in the tropical country of Malaysia to attain a degree of passive control, thus providing comfortable conditions. It can be deduced that there are five features of RBDB typology construction that directly influence thermal performance which lead to indoor thermal comfort. They are size of the space, opening, floor and roof heights, materials, open compound area, and building settings. Nonetheless, the percentage of thermal comfort is too low compared to suggested by ASHRAE 55 and ICOP, showing that it is not significant enough to be the reference for modern housing.

The primary aspect that generates this eventuate is the replacement of the original roofing material with zinc sheet. As suggestion, the zinc sheet can be replace with the ceramic roof tiles. It is because the ceramic material would provide better indoor thermal performance by reduce heat transmitted. This material could decreases up to 60% or less than asphalt shingles of heat which transmit from the ceramic tiles roofing into the ceiling (Miller et al., 2007). In addition, another elements that should be considered as part of the passive design strategies is the roof color. The majority of roof tiles in Malaysia are dark in color, which means that it absorbs more heat (Roslan et al., 2015). However, having natural ventilation devices has to assist to lessen the warmer indoor environment and occupants overcome the situation.

Therefore, to ought a justifiable finding, statistical adaptive (SA) models should be applied and recommended in further thermal comfort assessment. SA model is the advanced study to acknowledge thermal comfort based on particular environmental conditions. The findings from these models emphasize the value of post-occupancy data. Other than only evaluating the occupant's comfort level by measuring the indoor environment and verifying the result through the standards, the occupant's perception is also needed to enhance the understanding of the indoor environment. This survey will help verify and identify which thermal condition gives adequate performance to the occupants. In addition, adaptive comfort standard (ACS), an alternative adaptive model by ASHRAE 55 is advised to use for determining and analyzing permissible thermal conditions in occupant-controlled naturally conditioned spaces or natural ventilation (NV) buildings.

Additionally, to apprehend the different strategies which influence the indoor thermal pattern of the tested house, scientific evidence through computer simulation is suggested. The simulation should be graphically intelligiblly illustrated through the use of any software, such as computational fluid dynamic (CFD). Besides, the experiment could identify the best strategy to achieve thermal comfort for the tested house. Through this study can aspires to provide useful insights into effective climatic design strategies in a TMH. The findings will contribute to the scientific discussions on this subject towards sustainable practices in modern residential. Therefore, it is possible to reinvent the housing design process as long as people in this industry can cooperate to achieve the goal of sustainable housing and respond well to the local tropical climate. This is crucial to ensure that modern house designs for Malaysians are of good quality and fulfill the people's expectations of sustainable housing. Thus, it is aligned with the Twelfth Malaysia Plan (RMK12) Theme 3, where Malaysia aims to be a carbon-neutral country by advancing green growth and enhancing energy sustainability as early as 2050. Apart from it, the intelligent traditional construction techniques of the Malay house can be preserved and prolonged.

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# Sustainable Adaptive Reuse Strategy Evaluation for Cultural Heritage Buildings

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## ABSTRACT

Historical buildings are heritages that play a strategic role in the sustainable building environment need to be protected, and the continuation of the building stock from the past to the present should be ensured. With the concept of adaptive reuse, it is important that historical buildings gain new functional features with contemporary additions, ensure the continuity of cultures and carry the traces of the past to future generations. The aim of this study is to determine the adaptive reuse strategy of historic buildings, and to observe how contemporary additions are integrated to maintain a sustainable form of conservation. The research question of th study is how the contemporary additions that can meet the needs of the reuse of the historical buildings are applied. The building samples obtained through the literature review were evaluated in terms of physical aspects include criteria such as the size and mass of the additions, material selection, and the suitability of the existing historical building to the new function by using the comparative analysis method. It has been determined that although the designs of the additions are different from each other, most of the additions to the existing buildings are made for commercial and cultural purposes and involve steel and glass materials. The built environment can be revitalized as a result of bringing these buildings to society, using new functions and contemporary materials, and introducing economic, socio-cultural, and environmental innovations.

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## 1. Introduction

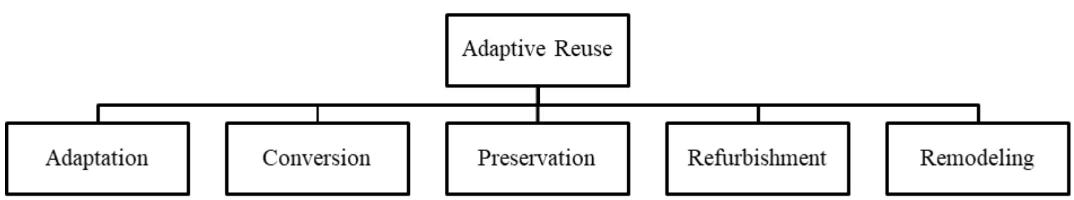
The concept of conservation is a multidimensional phenomenon that includes many components, and one of the most important features of conservation is keeping the historical environments alive with the values they carry. Although traditional methods are used as a protection method, adaptive reuse methods, which are differentiated by the developing material science and the desire for differentiation in design, are widely preferred. Adaptive reuse is a regulation that extends the life of buildings by enabling the use of existing buildings for different functional purposes (Mahtab-uz-Zaman, 2011). Many studies reveal that the adaptive reuse strategy is more sustainable based on economic, social, and environmental impacts compared to the typical demolition of buildings (Aigwi et al., 2022; Chan et al., 2020). One of the reusing an existing building instead of construction a new building, reduces material use, transportation cost, energy consumption, and environmental pollution. Thus, a significant contribution can be made to low carbon consumption and sustainability in nature (Toprak and Sahil, 2021). Since historical buildings were constructed with the conditions and techniques of the past, adaptation processes require various levels of intervention (Kutlu et al., 2022).

The adaptive reuse approach focuses on changing the useful and valuable features of the building with contemporary additions using different functions and materials (Shehata et al., 2015). From an economic point of view, it is often cheaper and faster to redevelop historic buildings with adaptive reuse rather than demolishing and rebuilding (Aigwi et al., 2018). In this case, which saves time, financial and structural costs are also reduced (Langston and Shen, 2007). With the re-functioning process for historical buildings, it is ensured that modern design requirements are added and the old building elements are preserved (Aigwi et al., 2020; Yuceer and Vehbi, 2014). Maintaining the existing building's structure and original features (Love and Bullen, 2009) or increasing the functionality of the historical building is one of the main purposes (Wong, 2016). The characteristics of cultures play a role in the change of architectural values (Suprapti et al., 2022; Rahmatulloh et al., 2020).

It is necessary for designers to create specific methodologies, risk management, and measures for adaptive reuse strategy, which has different challenges (Tam et al., 2016). The reuse of culturally valuable buildings in the city requires interdisciplinary thinking. Thus, it is possible to make evaluations where versatile solutions can be found against multi-faceted problems (Foster, 2020; Tafahomi and Nadi, 2020). Application of modern construction techniques instead of old construction techniques in versatile evaluation criteria (Kibert, 2007), the change of a certain part of the building rather than the transformation of the whole (Sandin et al., 2014), understanding its value in the building stock by obtaining realistic databases about the existing building with Building Information Modeling (BIM) technologies (Mustafa et al., 2019; Stephan and Athanassiadis, 2017) are essential and it should be considered to construct economically improving systems by observing the environmental effects of adaptive transformation with technological tools (Shindell, 2015).

Evaluation of cultural heritage buildings in the context of adaptive reuse is a complex process as it must be done without damaging the existing structure, and it is becoming increasingly popular because it is an important subject (Camocini and Nosova, 2017). Douglas (2006) defined this concept as any intervention in a building that goes beyond maintenance to alter its capacity, function or performance. Schmidt et al. (2009) described the adaptive reuse strategy as the reflection of a building and its ability to maximize life value by responding to the needs of the users. Plevoets and Van Cleempoel (2011) explained the adaptive reuse phenomenon as the most effective way of preserving historical buildings and transferring them to future generations. Tanaç Zeren (2013) explained her adaptive reuse strategy as the act of finding a new use for historic buildings that help define the character of societies. Elsorady (2014) defined the concept as renovating historical buildings in a way that allows contemporary activities, without harming the collective memory of the society and the original texture of the building. Tan et al. (2014) emphasized the adaptive reuse approach, the change and transformation of the building by preserving its basic structure and texture. Fiorani et al. (2017) explained the definition of adaptive reuse as a process related to the relations between orientations and spaces in addition to function change. Rodrigues and Freire (2017) defined the concept of adaptive reuse as the retrofitting process of old buildings for new uses. Depending on the definitions made, the terms associated with the adaptive reuse approach are given in Table 1.

**Table 1** Concepts associated with the adaptive reuse strategy (by the authors)




Conejos et al. (2016) proposed the principles regarding the building adaptation project in the decision processes in the building where adaptive reuse is applied. Yung and Chan (2012) interviewed practitioners involved in adaptive reuse projects in Hong Kong and explored sustainability factors. In this aspect, technological developments also play a role in decision processes in the adaptive reuse strategy, allowing quick decisions to be made. Multi-criteria techniques such as the space syntax method are used in facades and spatial organizations (Zaleckis et al., 2022; Rao et al., 2022).

It is also important to identify the actors according to the content of the project and their future use, analysis of the needs of the existing texture and region, classification of emergency and protection measures, proposals for replanning and new additions, and evaluation of adaptive reuse potentials (Mısırlısoy and Günçe, 2016). Adaptation criteria need to be met in the perspective of the symbolic value of the building and new potentials (Bottero et al., 2019). It also affects the circular city strategy in the field of sustainable development of unused or abandoned cultural heritages and rapid transformation of cities takes place (Della Spina, 2021; Clarke et al., 2020). Numerous factors should be considered for the most suitable solution among the different reuse suggestions. A sustainable reuse proposal should transfer the value of historical buildings to future generations, enrich the local culture and raise the economic level of the society. When evaluating the success of an adaptable reuse project; it is expected to offer a physical benefit to the building (Knoth et al., 2022).

In this study, the samples that were re-functionalized to add to the existing building stock by renewing the historical and cultural heritages with contemporary constructions and materials examined. After the literature review, the features of the concept of adaptive reuse were introduced, then inferences were made by making evaluations according to certain parameters in the building, depending on the material and method. In introduction part, information about adaptive reuse is given and literature studies are searched. In Section 2, researches in the architectural context are included by looking at the economic, socio-cultural and environmental aspects, which are the 3 important elements of the adaptive reuse strategy. In Section 3, the characteristics of sustainable building projects are introduced and comparative analyses are made. In Section 4, the information obtained as a result of the comparative analyses has been evaluated. In Section 5, a reference has been made for future work on the building stock, depending on the evaluations made.

## 2. Adaptive Reuse Features

Adaptive use of buildings is a concept associated with architecture, but with its new function, it also affects various disciplines such as civil engineering, urban planning and politics. From an architectural point of view, the adaptive reuse strategy is linked to deconstruction and material reuse (Chan et al., 2020). It can be defined in three general stages as deconstruction, soft stripping, complete structural disassembly and an individual disassembly project (Chini and Bruening, 2003). Deconstruction approach has two methods as destructive and non-destructive (Smith and Hung, 2015). The purpose of deconstruction is to take raw material from the physical infrastructure for reuse and recycling (Ilerisoy and Takva, 2017; Langston et al., 2008). The term material reuse includes component reuse and recycling (Chan et al., 2020). These concepts, which stand out in the adaptive reuse strategy, require the adoption of different approaches in different building types in terms of economic, socio-cultural and environmental aspects. Table 2 shows the multiple advantages of the adaptive reuse strategy based on sustainability principles.

**Table 2** The basic components of the concept of sustainability (by the authors)

| Economic | Socio-cultural | Environmental |
|---|---|---|
| Reducing economic costs | Positive impact on society and population | Protect from destruction |
| Financial growth | New sources of income | Waste reduction |
| Use of local resources | New job opportunities | Energy conservation |
| Economic investment opportunities | Preserve the history of buildings | Reducing urban degradation |
| Revival of the market | Strengthening national values | Adaptation to climate change |

New needs should be made in a contemporary language without degrading the original value of historical buildings, so as not to cause any confusion (Tabak and Sirel, 2022). Plevoets and Cleempoel argue that "adaptive reuse" have been started to use more frequently in the sense of urban, architectural and conservation strategy and sustainability of the biggest reasons for this. Concept of sustainability refuses the big scale demolitions and seeks the solution to guarantee ecological and socio-cultural pattern for the sake of future in transformation (Plevoets and Cleempoel, 2019).

In addition, the structural complexity of historic building projects, the environmental costs of demolition waste (Yuan et al., 2011) and regulatory requirements lead to indirect costs in the adaptation process (Wilkinson et al., 2009). In the context of socioeconomic developments, it is important to apply sustainable concepts (Niemczewska, 2020). From a socio-cultural point of view, the development of practical sustainable concepts for urban transformation planning plays a role in the protection of architectural heritage together with adaptive reuse (Alpopi and Manole, 2013). For this reason, the new use of the buildings ensures that the historical heritages that are inactive socio-culturally are brought to the society by reviving them (Esther Yakubu et al., 2017). Environmentally, adapting historical buildings to new uses supports the reduction of pollution (carbon dioxide emission) and energy consumption resulting from construction activities (Itard and Klunder, 2007). Environmental performances of the building such as indoor air quality, acoustic and thermal analysis may not be fully met in some cases, but social gains balance this situation (Chan et al., 2020). Innovative technologies applied in buildings within the scope of adaptive reuse, as passive environmental systems are not generally supported in historical buildings, bring sustainable solutions (Bullen, 2007). Thus, the life cycle of the building is also extended (Othman and Heba, 2018).

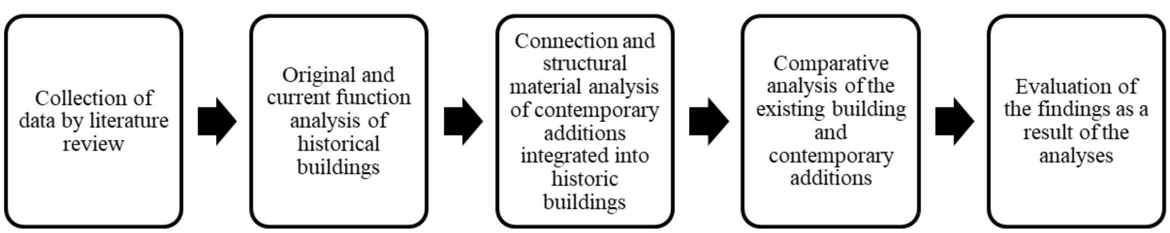
Adaptive reuse projects of historical heritage are a conservation method and approach to maintain the building values and prevent them from falling into ruin (Ali et al., 2018). These projects prevent the uncontrolled demolition of the building, balance the maintenance time and have a positive effect on urban construction by reducing land use (Abdulameer and Sati'Abbas, 2020). Historical streets also connect the community in terms of land use (Zahid and Misirlisoy, 2021). Adaptive reuse projects, which strengthen the bond between societies, provide modern needs and activities by ensuring that buildings reach future generations. Economically, the reuse of historical heritage buildings creates new opportunities in the fields of accommodation, commercial and cultural activities. These projects, which are also important from an aesthetic point of view, increase the demand for buildings in the residential area (Alhojaly et al., 2022). With adaptive reuse strategies against climate change, supportive designs such as improving energy efficiency and making plans for maintenance-related climate change adaptation can be created (Sesana et al., 2018). In addition, analyses can be made depending on greenhouse gas emissions, fossil fuel, and water consumption (Assefa and Ambler, 2017).

Contemporary use of immovable heritage aims to develop by considering sustainable development for both designers, engineers and institutions, but developing a strategy without damaging immovable historical building heritage is a challenging process. It is necessary to draw a road map by taking into account sensitive building elements in buildings that have a social, political, or religious meaning as well as a symbolic value (Lo Faro and Miceli, 2019). Compliance with building codes, conservation laws, temporary supports to stabilize building elements, plumbing and HVAC systems, foundation and roof mechanisms, and space access are criteria that require detail and expertise in adaptive reuse projects (Hein and Houck, 2008). Building codes and regulations/legal restrictions, high redevelopment costs and construction delays, physical constraints, complexity and technical difficulties, inaccuracy of information and drawings, lack of qualified personnel, stability of production and development criteria, commercial risks, uncertainties, and management problems negatively affect the reuse of the building (Eray et al., 2019). In order to avoid making dangerous choices due to the wrong and risky use of resources, resources should be optimized and focused on getting the maximum benefit from society (Dell'Ovo et al., 2021).

## 3. Methodology

In the adaptive reuse strategy, contemporary additions should be applied without disturbing the texture and structure of historical buildings. From an architectural point of view, the combination of innovative materials and decisions for design and aesthetics brings sustainable solutions. The research question of the study is how the contemporary additions that can meet the needs of the historical building are applied in the most common historical buildings in the literature, which materials are used in terms of structure, and how the combination of old-new harmony is created. In the context of multiple evaluation criteria, the shape and plan geometry, contemporary addition size, contemporary addition material, facade features, function change, symmetry and proportion/size compliance were taken into account in ensuring the old-new harmony (Bottero et al., 2019; Wong, 2016; Conejos et al., 2013). Data were collected through literature review and these parameters were evaluated using comparative analysis. The flow chart of the study is given in Table 3.

**Table 3** Flow chart of the study (by the authors)




In this study, historical buildings with high historical value and symbols of countries were selected. Additionally, historical buildings where adaptive reuse strategy is applied with contemporary additions constitute the scope of the study. These buildings were actively used in the period they were built and today they are adapted to meet the usage needs and constitute sustainable building stocks. They are the most known and iconic structures that can be found in the academic literature. With the implementation of the adaptive reuse strategy, the addition of innovative materials contributed to sustainability.

The buildings examined according to the information obtained from the literature review were built between the 15th and the 20th century (Table 4). Six of the buildings are located in the United Kingdom (UK), five in Germany, three in the United States (USA) and others in different countries.

**Table 4** Buildings with historical and cultural value where the adaptive reuse strategy is applied (Soliman and Aggour, 2018; Fisher-Gewirtzman, 2016; Fiedler and Schuster, 2016; Mısırlısoy, 2011)

| No | Project | Year of Construction | Year of Transformation | City | Country |
|---|---|---|---|---|---|
| 1 | German Parliament Building | 1894 | 1999 | Berlin | Germany |
| 2 | Jewish Museum | 1933 | 1999 | Berlin | Germany |
| 3 | Great Court at the British Museum | 1820-1850 | 2000 | London | UK |
| 4 | Documentation Center Nazi Party Rally Grounds | 1930s | 2002 | Nuremberg | Germany |
| 5 | Higgins Hall, Pratt Institute | 1869 | 2005 | Brooklyn | USA |
| 6 | Gemini Residence | 1909 | 2005 | Copenhagen | Denmark |
| 7 | The Hearst Tower | 1928 | 2006 | New York | USA |
| 8 | Caixa Forum | 1899 | 2007 | Madrid | Spain |
| 9 | Moritzburg Museum | 1400s | 2008 | Halle | Germany |
| 10 | Rotermann Carpenter's Workshop | 1904 | 2009 | Tallinn | Estonia |
| 11 | Rotermann's old and new flour storage | 1904 | 2009 | Tallinn | Estonia |
| 12 | Museum Der Kulturen | 1849 | 2010 | Basel | Switzerland |
| 13 | National Maritime Museum | 1656 | 2011 | Amsterdam | Netherlands |
| 14 | Louviers Music School Rehabilitation and Extension | 1659 | 2012 | Louviers | France |
| 15 | 192 Shoreham Street | Victorian age | 2012 | Sheffield | UK |
| 16 | Museum de Fundatie | 1938 | 2013 | Zwolle | Netherlands |
| 17 | Bombay Sapphire Distillery | 1724-1990 | 2014 | Laverstoke | UK |
| 18 | CRICOTEKA Museum of Tadeusz Kantor | 1900s | 2014 | Krakow | Poland |
| 19 | Seona Reid Building | 1909 | 2014 | Glasgow | UK |
| 20 | London Water Tower House | 1867 | 2015 | London | UK |
| 21 | Elbphilharmonie | 1875 | 2016 | Hamburg | Germany |
| 22 | Antwerp Port House | 1990s | 2016 | Antwerp | Belgium |
| 23 | Tate Modern | 1947-1963 | 2016 | London | UK |
| 24 | Zeitz MOCAA | 1921 | 2017 | Cape Town | South Africa |
| 25 | 44 Union Square | 1928 | 2020 | New York | USA |
| 26 | Convent Saint François | 1480 | 2021 | Sainte Lucie de Tallano | France |

The examined buildings were numbered and classified according to the first year of construction and the year of transformation as a result of the adaptive reuse strategy and are shown in Table 4, in which the buildings are listed chronologically according to the year of transformation. Contemporary approaches, technology opportunities, expanding material range, and the desire for differentiation in design have led to different applications in historical buildings. The current state of the buildings is given in Table 5 according to their functions and the added innovative material properties.

**Table 5** Changing features of adaptive reuse projects (Alshawaaf and Lee, 2021; Pieczka and Wowrzeczka, 2021; Takva and İlerisoy, 2021; Šijakovic and Peric, 2018; Kim, 2018)

| No | Original function | Current function | Material of the added structure |
|---|---|---|---|
| 1 | Parliament Building | Parliament Building | Steel frame, clear glazing dome |
| 2 | Courthouse | Museum | Steel and reinforced concrete, glass |
| 3 | Museum | Museum, library | Steel frame, triangle freeform glass structure consisting of panels |
| 4 | Nazi Rally building (meeting place) | Documentation Center | Steel frame and glass |
| 5 | Education (academic) | School of Architecture in Pratt Institute | Channel-glass, six pre-cast concrete columns, thick steel beams |
| 6 | Frosilos seed silos | Housing | Concrete core mass, glass facade, and glass roof |
| 7 | Mixed-use (Office etc.) | Hearst corporation headquarters (office) | Recycled steel, glass facade |
| 8 | Power station | Contemporary art museum, | Three main concrete cores, with oxidized cast-iron steel plates |

| | | | |
|---|---|---|---|
| | | cultural center | cladding |
| 9 | Castle | Art museum | Steel structure and cladding, glass facade |
| 10 | Carpentry workshops | Office, commercial | Reinforced concrete core mass, steel frame and glass |
| 11 | Industrial building (flour storage) | Office, commercial, storage | Steel constructed glass bridges, cor-ten coating |
| 12 | Museum | Ethnographic museum | 10,000 three-dimensional, hexagonal glazed ceramic tiles, steel frame |
| 13 | Maritime warehouse | Museum | Steel frame and glass roof |
| 14 | Ancient monastery | Music school | Precast concrete panel walls, laminated glass, stainless steel |
| 15 | Factory | Mixed-use (restaurant and studio office) | Natural wood and plasterboard walls, lightweight steel frame with composite slabs |
| 16 | Courthouse | Art museum | 8 steel column structure, three-dimensional ceramic facade cladding |
| 17 | Corn mill building | Distillation Center | Two new glasshouses |
| 18 | Power station | Modern art gallery, museum | Steel truss frame, reinforced concrete core, glass facade |
| 19 | Art School | Glasgow School of Art | Translucent glass envelope and concrete structure |
| 20 | Water tower | Housing | A new elevator, glass-fronted cube, cast-iron structure |
| 21 | Warehouse (cocoa, tobacco, and tea etc.) | Cultural center | Wavy glass mass consisting of panels, steel structure |
| 22 | Fire station | Headquarter of port | Three sculptured concrete pillars, triangular glazed surface |
| 23 | Power station | Contemporary art museum | Glass beam placed on the roof, steel truss structure |
| 24 | Grain silo complex | Contemporary art museum | Three-dimensional glass facade, concrete structure, steel stairs |
| 25 | Tammany hall headquarters, performing arts hall | Commercial use | Steel frame, glass dome |
| 26 | Castle, monastery | Monastery | A hollow copper structure |

Historical buildings, which are an important part of urban systems, shape the use of the region at the city level by creating an environmental impact in terms of their functions (Wang and Liu, 2021). Renewal of the building function is a criterion for achieving the purpose of conservation apart from the main purpose in the adaptive reuse strategy, considering it as a cultural action as well as technical competence (Semprini et al., 2017). In the study, the renovation of new functions to the existing use of the building makes the building more attractive and more visited. The need for new functions in buildings to meet the physical capacity and the provision of mechanical and technical conditions in line with this need play a role in the longevity of the structure (Hong and Chen, 2017). The presence of buildings with commercial and cultural functions, especially in metropolises, has also been reflected in new functions in the buildings after the adaptive reuse strategy (Wang and Nan, 2007). The old and new functions of the historical buildings examined are given in Table 6.

**Table 6** Original and new uses of the studied buildings (by the authors)

| | **Original function** | | | | | | | | **Current function** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Project no | Public | Residential | Educational | Commercial | Religious | Industrial | Military | Cultural | Public | Residential | Educational | Commercial | Religious | Industrial | Military | Cultural |
| 1 | ■ | | | | | | | | ■ | | | | | | | |
| 2 | ■ | | | | | | | | | | | | | | | ■ |
| 3 | | | | | | | | ■ | | | | | | | | ■ |
| 4 | ■ | | | | | | | | | | | | | | | ■ |
| 5 | | | ■ | | | | | | | | ■ | | | | | |
| 6 | | | | | | ■ | | | | ■ | | | | | | |
| 7 | | | | ■ | | | | | | | | ■ | | | | |
| 8 | | | | | | ■ | | | | | | | | | | ■ |
| 9 | | | | | | | ■ | | | | | | | | | ■ |
| 10 | | | | ■ | | | | | | | | ■ | | | | |
| 11 | | | | ■ | | ■ | | | | | | ■ | | ■ | | |
| 12 | | | | | | | | ■ | | | | | | | | ■ |
| 13 | | | | ■ | | ■ | | | | | | | | | | ■ |

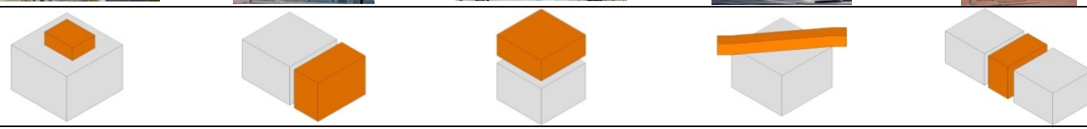
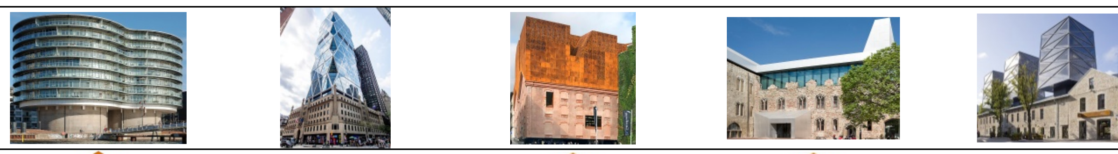
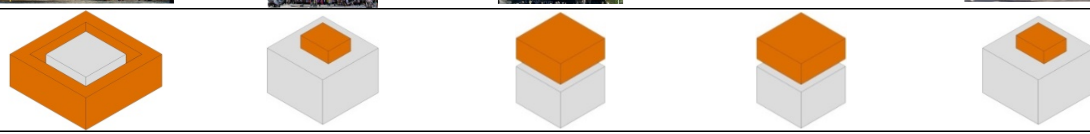
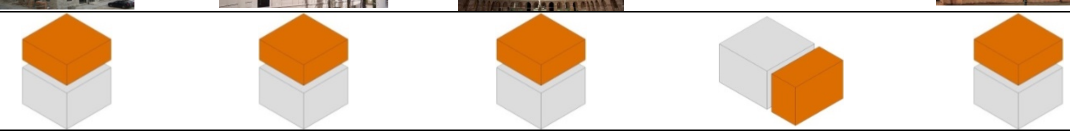
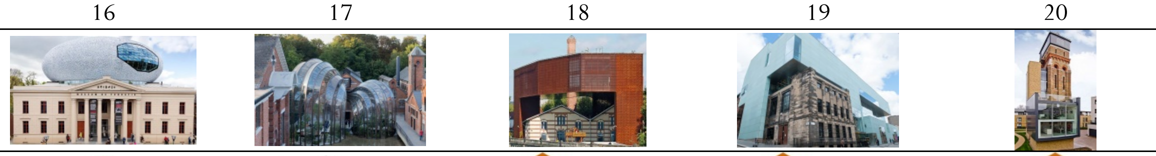
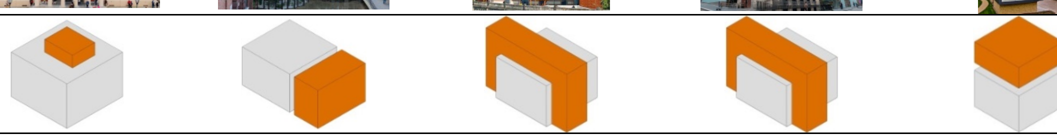
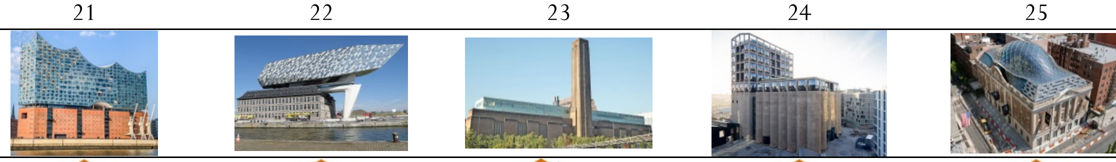
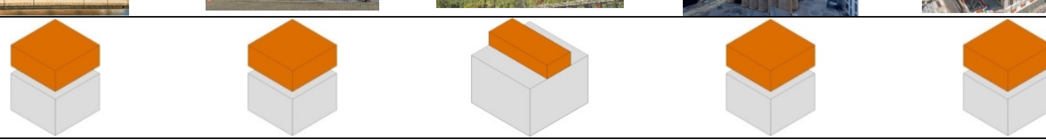
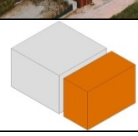
| | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 14 | | | | | ■ | | | | | | ■ | | | | | |
| 15 | | | | ■ | | ■ | | | | | | ■ | | | | |
| 16 | ■ | | | | | | | | | | | | | | | ■ |
| 17 | | | | ■ | | ■ | | | | | | ■ | | ■ | | |
| 18 | | | | | | ■ | | | | | | | | | | ■ |
| 19 | | | ■ | | | | | | | | ■ | | | | | |
| 20 | | | | | | ■ | | | | ■ | | | | | | |
| 21 | | | | ■ | | ■ | | | | | | | | | | ■ |
| 22 | ■ | | | | | | | | | | | ■ | | | | |
| 23 | | | | | | ■ | | | | | | | | | | ■ |
| 24 | | | | | | ■ | | | | | | | | | | ■ |
| 25 | | | | ■ | | | | ■ | | | | ■ | | | | |
| 26 | | | | | ■ | | ■ | | | | | | ■ | | | |

Since the re-using building requires more space and different spatial qualities, the transformation must be solved with a different addition from the old structure (Ilerisoy and Soyluk, 2013). In this case, the designer should prevent the planned new addition building from competing with the historic building. In order to prolong the life of the building, the existing building components must be preserved and integrated into the contemporary construction according to the new function (Gusmerotti et al., 2019). In order to reduce design constraints caused by material changes, it is important to apply design and process standardization and monitor the compatibility of existing and new materials (Anastasiades et al., 2021). Analyses should be made by looking at the physical properties, protection status, and technical performance of the existing building material (Addis, 2012). The reuse of materials and the integration of contemporary building materials in an abandoned historical building with the potential for re-functioning should be arranged considering the function of the spaces (Monsù Scolaro and De Medici, 2021). Table 7 shows the use of contemporary and innovative materials added to the structures. In Table 8, the location of the contemporary constructions added to the historical buildings is given.

**Table 7** Innovative material properties of regenerated structures as a result of adaptive reuse (by the authors)

| Project no | Wood | Reinforced concrete (RC) | Copper | Steel | Composite | Glass | Ceramic |
|---|---|---|---|---|---|---|---|
| 1 | | | | ■ | | ■ | |
| 2 | | ■ | | ■ | | ■ | |
| 3 | | | | ■ | | ■ | |
| 4 | | | | ■ | | ■ | |
| 5 | | ■ | | ■ | | ■ | |
| 6 | | ■ | | | | ■ | |
| 7 | | | | ■ | | ■ | |
| 8 | | ■ | | ■ | | | |
| 9 | | | | ■ | | ■ | |
| 10 | | ■ | | ■ | | ■ | |
| 11 | | | | ■ | | ■ | |
| 12 | | | | ■ | | | ■ |
| 13 | | | | ■ | | ■ | |
| 14 | | ■ | | ■ | | ■ | |
| 15 | ■ | | | ■ | ■ | ■ | |
| 16 | | | | ■ | | ■ | ■ |
| 17 | | | | ■ | | ■ | |
| 18 | | ■ | | ■ | | ■ | |
| 19 | | ■ | | | | ■ | |
| 20 | | | | ■ | | ■ | |
| 21 | | | | ■ | | ■ | |
| 22 | | ■ | | ■ | | ■ | |
| 23 | | | | ■ | | ■ | |
| 24 | | ■ | | ■ | | ■ | |
| 25 | | | | ■ | | ■ | |
| 26 | | | ■ | | | | |

**Table 8** Integration of contemporary additions to selected historical buildings (by the authors)

| | | | | | |
|---|---|---|---|---|---|
| **Project no** | 1 | 2 | 3 | 4 | 5 |
| **Project image** |  | | | | |
| **Structural addition** |  | | | | |
| **Project no** | 6 | 7 | 8 | 9 | 10 |
| **Project image** |  | | | | |
| **Structural addition** |  | | | | |
| **Project no** | 11 | 12 | 13 | 14 | 15 |
| **Project image** |  | | | | |
| **Structural addition** |  | | | | |
| **Project no** | 16 | 17 | 18 | 19 | 20 |
| **Project image** |  | | | | |
| **Structural addition** |  | | | | |
| **Project no** | 21 | 22 | 23 | 24 | 25 |
| **Project image** |  | | | | |
| **Structural addition** |  | | | | |
| **Project no** | 26 | | | | |
| **Project image** |  | | | | |
| **Structural addition** |  | | | | |

In the adaptive reuse strategy, there are four different methods in which the exterior of the building is renewed and the interior spaces are protected, the interior spaces are renewed and the exterior is preserved, the additions shaped according to the needs of the users are made in the existing structure, and only certain parts of the interior are renewed (Tam and Hao, 2019). Architectural design plans can also be changed according to these methods. It is important to develop a reuse concept in line with the principle of sustainability. Adaptable reuse and transformation of existing buildings as a task within the architectural discipline reaches effective solutions with minimum physical interventions, efficient management of existing building materials, and environmentally friendly design of building components in accordance with the principle of efficiency of resources in the context of sustainability, as well as interior architectural design (Celadyn, 2019). While making design plans in architectural design systematics, insertion, intervention, or installation processes are also required (Brooker and Stone, 2019). In these design plans, it is necessary to be aware of the changes and transformations that occur in historical cycles and to develop appropriate legal and design methods. In Table 9, a comparative analysis of the buildings examined according to their architectural design features has been made. The decisions taken during the design process should not cause permanent damage to the building and should increase the value of the historical building in line with sustainability. The criteria in the table are an indication of the direction of the basic architectural approaches in the adaptive reuse phase.

**Table 9** Comparison of structures based on architectural criteria (by the authors)

| Project no | Shape and plan geometry change | Width change of added structure | Structural material change | Facade material change | Facade colour change | Facade texture change | Function change | Symmetry | Proportion/size compliance |
|---|---|---|---|---|---|---|---|---|---|
| 1 | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 2 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| 3 | ■ | | ■ | | | | | | ■ |
| 4 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| 5 | | | ■ | ■ | ■ | ■ | | ■ | ■ |
| 6 | ■ | ■ | | ■ | ■ | ■ | ■ | ■ | ■ |
| 7 | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 8 | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 9 | | | ■ | ■ | ■ | ■ | ■ | | |
| 10 | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 11 | | | ■ | ■ | ■ | ■ | | ■ | ■ |
| 12 | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 13 | | | ■ | | | | ■ | | |
| 14 | | | ■ | ■ | ■ | ■ | ■ | | ■ |
| 15 | | | ■ | ■ | ■ | ■ | ■ | | ■ |
| 16 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| 17 | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 18 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| 19 | ■ | ■ | ■ | ■ | ■ | ■ | | | |
| 20 | | | ■ | ■ | ■ | ■ | ■ | | |
| 21 | | | ■ | ■ | ■ | ■ | ■ | | |
| 22 | ■ | ■ | ■ | ■ | ■ | ■ | ■ | | |
| 23 | | ■ | ■ | ■ | ■ | ■ | ■ | | |
| 24 | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |
| 25 | ■ | | ■ | | | | ■ | | |
| 26 | | | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

## 4. Findings

During the examination of the buildings' function change, which are listed chronologically, it can be said that the historical buildings were built mainly with commercial and industrial functions, and after the transformation, the industrial use decreased and the density in commercial and cultural functions increased. When looking at innovative building materials as a result of the adaptive reuse strategy, it has been observed that the constructions are predominantly made of steel and glass materials, and in addition to this, reinforced concrete building materials are also used in buildings at an average level. Apart from this, wood, copper, composite, and ceramic construction materials are rarely preferred. The integration of contemporary additions to the existing structure is generally positioned on the building mass. Formations in the form of a new structure or a top cover are seen on the existing structure.

In the context of architectural criteria, it was determined that the shape and plan geometry and the width of the added structure changed in approximately half of the buildings, the structure and facade materials changed in almost all buildings, and there were functional changes. In addition to these, it was determined that the symmetry is generally not preserved between the existing and contemporary buildings, asymmetry is more common, and structures with similar features in terms of ratio/size are less common. When considered typologically in general terms, it has been determined that construction systems designed with different shapes and geometries, built with steel and glass building materials for commercial and cultural purposes, located on the historical building are preferred in the context of adaptive reuse.

Considering the information obtained from the literature, academic studies in which the adaptive reuse strategy is applied are examined together, the function, the structural features of the contemporary additions, material and form configurations are examined with comparative analyses are limited. The detailed analysis of the functional and mass changes of historical buildings with the comparative analysis technique is an archive and can be seen as a contribution to the discipline of architectural preservation. The difference of the study from other studies in the literature is that historical building heritages are analyzed in detail with the content analysis method. The scale of the building stock in which the adaptive reuse strategy can be applied is wide. However, the important symbols of the countries with high historical value were examined. In this aspect, the limitation of this study has been drawn.

## 5. Conclusion

Adaptive reuse projects, where traditional and modern construction systems meet at the same point, form a bridge between the past and the future. In these projects, where traditional construction techniques and building materials are combined with modern and contemporary construction techniques and building materials, long-lasting structures are obtained within the framework of the sustainability principle. The return to active use of abandoned historical buildings, which have symbolic, cultural, religious, social, economic, environmental, and socioeconomic values in terms of architecture, by preserving their architectural and structural features, ensures that the region and the people of the region become active. Considering that demolition and rebuilding of buildings is more costly and in terms of sustainability, the adaptive reuse strategy is seen as an important and advantageous method in terms of maintaining the integrity of the city. In this study, the architectural features of the historical buildings in which the adaptive reuse strategy was applied were determined and analyzed. The importance of the study is to bring together adaptive reuse projects of important historical buildings selected from different countries, to analyze and compare their architectural and structural features in the context of sustainable conservation aspect. Findings on which architectural features are taken into account in adaptive reuse projects have been obtained. By increasing the use of innovative sustainable materials in buildings, it is ensured that they are long-lasting. The continuation of the use of historical buildings at strategic points prevents the disruption of order by maintaining the balance of the city and the region. In a sustainable environment, adaptive reuse strategies are evaluated specifically for the building and passed on to future generations, which also plays an important role in the development of the building stock. Considering the adaptive reuse strategies with this study, the application of contemporary additions will constitute a guiding reference for designers and researchers in the context of its relationship with historical buildings. Based on this study, it is thought that analysis methods will be developed in adaptive reuse projects for future studies.

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# Framework for Fire Safety Management of Hotels in Nigeria: A Structural Equation Modeling Approach

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## ABSTRACT

Recent findings indicate Nigeria is among the top countries with devastating consequences of fire incidences. The volatile position of Port-Harcourt as an oil-producing capital city is seen as one of the reasons why fire disasters occur in hotels, among other high rises institutional building structures. This study, therefore, explored the factors responsible for the high incidences of fires in Port-Harcourt, Nigeria. As phenomenological research involving humans, a 5-point Likert scale cross-sectional questionnaire survey instruments were developed using online Google forms to evaluate people's awareness, identify the material factors that promote fire incidents, and assess the present policy and standards to control fire incidents. The ordinal scaled data collected from 108 respondents were tested to be reliable with a Cronbach alpha of 0.958 using the SPSS Statistic software and further analyzed using the Structural Equation Modelling approach. Results show that hotel workers in Port-Harcourt are aware of fire safety management issues, though periodic retraining is required as new technologies evolve. Safety standards are also relatively maintained in the placement of equipment power points, extinguishers, and emergency controls. However, the significant causes of the fire were attributed to electrical and mechanical devices installed and utilized on the hotel premises. While the study calls for the installation of high-quality equipment in hotels, more inquiry is needed to check the reliability of individual equipment. A framework was finally conceptualized for further research and replicating the study in other contexts. This study's findings are essential to hotel entrepreneurs and managers, fire experts, building designers, and researchers.

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## 1. Introduction

Fire safety management can be described as applying fire protection measures to research, evaluation, and control of fire using policy, standards, and tools, among other information available (Furness & Muckett, 2007; Sari, Rafrita, Rahayuningsih, & Alfianto, 2019). It may also be viewed as an organized plan for ensuring that people's responsibilities under the fire safety directive are met, typically through a fire safety policy (Della-Giustina, 2014).

Though following fire safety norms and guidelines does not necessarily imply that fires are wholly avoided, fires are limited so that loss of lives and property are put to the barest minimum. Natural fire safety regulations have existed for centuries, with new standards developed chiefly in response to disasters (Barau & Barau, 2017; Maluk, Woodrow, & Torero, 2017). When a fire is contained and regulated, it naturally keeps people warm while also allowing for the creation of novel resources through reprocessing and other means of production, as without heat and fire, civilization would be adversely different. However, it can also destroy lives, buildings, and companies when it goes out of control (Hassanain, Al-Harogi, & Ibrahim, 2022; Wang, Li, Feng, & Yang, 2021). When people exposed to fire outbreak are psychologically affected, the trauma kills in most situations more than the physical burns (Nimlyat, Audu, Ola-Adisa, & Gwatau, 2017; Ogochukwu, Oduduabasi, & Anake, 2019). Every structure contains something that might easily cause a fire, and it is nearly impossible to eliminate the possibility of a fire in a building. This informs the preference for adopting the term "fire-resistant" against "fireproof" when describing building materials (Chen & Liew, 2003). Building damage from a fire is often difficult to repair. Even when fixed, it last just for a short time. As a result, fire may be seen as a decent servant but a nasty boss, a valuable tool with a dreadful nightmare.

Generally, fire disasters are one of the world's most prevalent and damaging calamities that have proven difficult to address, especially in developing countries (Agbola & Falola, 2021; Salazar, Romão, & Paupério, 2021). Due to rapid global technological development, the frequency of building fires has altered significantly. Nevertheless, in terms of their severity and resilience, they have become a growing source of concern in recent years. Reports indicate that there have been over a hundred million fire incidences between 1993 and 2020, with 7-8 million occurrences and 70-80 thousand deaths (Brushlinsky, Ahrens, Sokolov, & Wagner, 2016; Brushlinsky, Sokolov, Wagner, & Messerschmidt, 2022). In the 2022 report, the Czech Republic tops the frequency of fire calls, Cyprus in number per thousand, Russia in total deaths, and Belarus in death per hundred population. Citing a media article by Tolofari in 2010, Nimlyat et al. (2017) put the annual fire outbreak in Nigeria at about 7,000, with resultant deaths of over 1,000 persons (p.775). However, the recent report on World Fire Statistics by Brushlinsky et al. (2022) indicates that Nigeria recorded 2,056 fire occurrences and 147 deaths in 2020 (p.26). According to the report, Nigeria is not among countries with the highest frequency of fire incidences, the country comes only to Belarus in the number of deaths per hundred fire occurrences (p.40). Explaining further, Nimlyat et al. (2017) link the improvement in the number of fire occurrences to the recent approval of the National Building Code (NBC) and National Fire and Safety Code (NFSC) by the Nigerian Government.

Though fire incidences are mostly under-reported, the reported 2,056 incidents in Nigeria (Brushlinsky et al., 2022) make the average for the 36 states and the Federal Capital Territory (FCT), amounting to 56 cases. Considering the numerous fire occurrences due to oil exploration, accidents, and other cultural practices, Nwaichi (2022) puts the frequency of fire incidents in Rivers State – Nigeria, at 100 per year. It is on record that the great fire of Ogoniland destroyed one-tenth of the city in 1999, including hotels and other high-rise structures. Also, studies on fire outbreaks in hotel buildings are still emerging due to inadequate empirical research on fire safety management. Although fires affect various building structures, Ronchi and Nilsson (2013) advise that hotel employees must be ready to act swiftly, as the first five minutes of a fire emergency are essential to its control. Even though hotel buildings have the most sophisticated fire safety features, human factors such as indifference, ignorance, or a deficiency in design and safety awareness are usually blamed for fire outbreaks and poor enhancement of fire safety.

Furthermore, inadequate policy implementation and fire safety awareness affect the attitude of staff and workers in the hotel buildings, with numerous negative consequences for the community and environment. The attitude of employees in the workplace depends on their awareness of occupational hazards. Consequently, there is a critical requirement to evaluate the degree of knowledge of and application of fire safety policies at the hotel buildings. In their study on reducing the likelihood of fire and mitigating repercussions of its occurrences, Sun and Luo (2014) posit that "Good management of fire safety" is essential to lower the probability of fire occurrence and to mitigate the consequence if a fire does occur (p.492).

This study attempts to determine the most critical aspects of fire safety management that impact hotel building occupants' fire safety and actions to enhance it. It sets to statistically measure the workers' awareness of fire hazards in hotels and assess fire incidents relating to cultural and safety management standards, using the Structural Equation Modelling (Tuhul et al.) approach. The study suggests a unified framework for workers' awareness, fire assessment, hotel fire incidents, cultural practices, and safety standards in hotel fire management. The suggested framework is distinctive as it incorporates human and material factors and policy and management standards. Detailed recommendations are offered to solve these boundaries using the suggested fire safety framework to demonstrate the applicability of enhancing fire safety in Port Harcourt, Rivers State, Nigeria. As a result, the design and cost-effectiveness of recommended remedies are given specific attention, highlighting the need for additional research and training to improve hotel building safety.

## 2. Methodology

The methodology for this study involves a cross-sectional survey, where one-time data was collected from different gender and age grades. The data were analyzed and ranked through the

Confirmatory Factor Analysis (CFA) approach that forms the first-order level of the Structural Equation Modelling (Tuhul et al.) (Aule, Majid, & Jusan, 2022a), using the Analysis of Moment of Structures (AMOS) software.

## *2.1 Data Collection*

The data for this study was collected from varying types of workers in hotels, motels, guest houses, restaurants, and bars in Port-Harcourt – Nigeria. The different hospitality sectors formed a basis for the stratified probability sampling, where data was drawn from each population. Closed-ended structured questionnaires were utilized as the primary data source for hotel fire safety management. The structured questionnaires consist of a series of questions with multiple-choice options targeted to systematically gather valuable information from respondents on fire safety management in hotels directly from respondents. Compared to other data collection methods, the technique is more straightforward and less costly, requiring simplified effort from the researcher and undue pressure of probing physical enquiry from participants.

The five-point Likert-scaled ordinal survey instrument was grouped into eight sections: A, B, C, D, E, F, G, H, and I. Section A entailed gathering demographic information on the respondents, as presented in Table 1. The other sections collected data on workers' work experience, awareness of fire safety, management commitment to fundamental causes of fire, observance of basic fire safety policy, assessment of fire incidents, cultural practices, and fire safety management, respectively. In completing the survey, statements were made for respondents to select their choice on a 1 to 5 rating scale, from strongly disagree (SD), disagree (D), undecided (U), agreed (A), and strongly agreed (SA), in that order.

**Table 1** Respondents' demographic data distribution

| **Description** | **Category** | **Frequency** | **Percentage (%)** |
|---|---|---|---|
| Gender | Male | 60 | 55.6 |
| | Female | 48 | 44.4 |
| Age Range | 20-30 | 12 | 11.1 |
| | 31-40 | 44 | 40.7 |
| | 41-50 | 40 | 37.0 |
| | 51 & above | 12 | 11.1 |
| Educational Background | Secondary School/High School | 4 | 3.7 |
| | Graduate/College | 60 | 55.6 |
| | Postgraduate (Master/Ph.D.) | 44 | 40.7 |
| Hotel apartment | Standard High-rise Hotel | 20 | 18.5 |
| | Medium Standard (Motel) Hotel | 24 | 22.2 |
| | Restaurant and Bar | 8 | 7.4 |
| | Guest House | 8 | 7.4 |
| | Others | 48 | 44.4 |
| Hotel's year | 0-5yr(s) | 28 | 25.9 |
| | 6-10yrs | 48 | 44.4 |
| | 11-15yrs | 20 | 18.5 |
| | above 15yrs | 12 | 11.1 |

For quick and efficient delivery in line with modern practices, the online Google form was utilized for packaging and delivering the survey, conducted between July and September 2022. With the online resource, respondents were required to "click" the option corresponding to their answer choice. The survey was designed to exclude people without work experience in a hotel from the first question. The "required" constraint was also employed to manage occurrences of "missing data," where respondents may leave out some questions unanswered.

A paragraph space was also provided toward the end of the survey section for unstructured feedback from respondents regarding the issue under study. Some academic specialists and other experienced researchers assessed the survey questionnaire to ensure content reliability further. The questionnaire was, therefore, thoroughly reviewed for clarity, readability, accuracy, comprehensibility, and consistency. Finally, a link to the survey was generated and shared with some known hotel workers, who then snow-balled it to colleagues, official groups, and other respondents with hotel work experience in Port Harcourt, Rivers State, Nigeria. A total of 108 completed responses were received from the online ordinal scale survey. With about 50% internet coverage in Nigeria and a high cost of access, in addition to limited workers in hotels, the returned data was deemed sufficient to carry out the study.

### *2.2 Data Analysis*

The dataset obtained from the online survey was first subjected to some descriptive analysis in the form of percentages, tables and charts using the Statistical Package for Social Science (SPSS). Preliminary tests were performed on the data to check redundant respondents that selected the same option for all questions, outliers whose responses do not correlate with others, variable commonalities, reliability, and validity. However, as shown in Table 2, a Cronbach's alpha of 0.954 was attained in the collected data for this study, above the 0.7 thresholds appropriate for utilizing a data set for the subsequent statistical procedure. Furthermore, the Principal Component Analysis (PCA) produced a Kaiser-Meyer-Olkin (KMO) value of 0.66, above the required minimum of 0.6 measure (Achoba, Majid, & Obiefuna, 2021a; Aule, Majid, & Jusan, 2022b). Bartlett's Test of Sphericity also produced a significant 0.000 value, confirming the suitability of data for SEM.

**Table 2** High Cronbach Alpha showing Internal Reliability of Collected Data

Reliability Statistics

| Cronbach's Alpha | Cronbach's Alpha Based on Standardised Items | N of Items |
|---|---|---|
| 0.954 | 0.958 | 49 |

Case Processing Summary

| | | N | % |
|---|---|---|---|
| Cases | Valid | 108 | 100.0 |
| | Excluded | 0 | 0.0 |
| | Total | 108 | 100.0 |

a. Listwise deletion based on all variables in the procedure.

Survey data is reliable, with a Cronbach alpha greater than 0.7

Structural equation modelling (Tuhul et al.) assesses intangible impressions, such as values, accomplishments, esteem, preferences, and pleasure, which cannot be measured using some physical equipment (Aule et al., 2022a). Since the abstract qualities of people cannot be measured directly like physical entities, such as the number of people, weight, height, cars, and temperature, among others, they can effectively be measured with an ordinal scale (Kline, 2016). As a result, Achoba et al. (2021) view the CFA and SEM are instruments to explore and test correlations in ordinal scale data, particularly in social science studies.

Despite having different names in the same family, such as covariance structure modelling or analysis (Kline, 2016), SEM is frequently carried out in two processes known as orders. The two components are the first-order CFA and the second-order SEM. In most cases, CFA requires generating path diagrams and covariances before loading the factors, observed or measured variables. The loaded CFA model is then run and examined to remove insignificant components with less than 0.5 standardized regression weights (Achoba et al., 2021a; Achoba, Majid, & Obiefuna, 2021b; Aule et al., 2022a). The first-order CFA is complete when model goodness-of-fit is attained, and the criteria for reliability and validity are met. The second order creates a comprehensive model using the results of the SEM, which generates a series of dependent relationships between a group of concepts or constructs that are each represented by several quantifiable variables (Malhotra, 2020). This study will, however, be limited to the first-order CFA since the objective does not include formulating a hypothesis for statistical testing relationships.

## 3. Results and Discussion

The general model for fire safety management of hotels in Nigeria is presented in Figure 1. It is developed based on the ordinal variables utilized in the SEM analysis, excluding the categorical constructs of biodata and years of hotel experience. Discussion of the results will be based on the six independent variables of safety awareness, fire incidence, hotel policies, fire assessment, cultural and safety practices, and the dependent construct of overall hotel fire safety management.

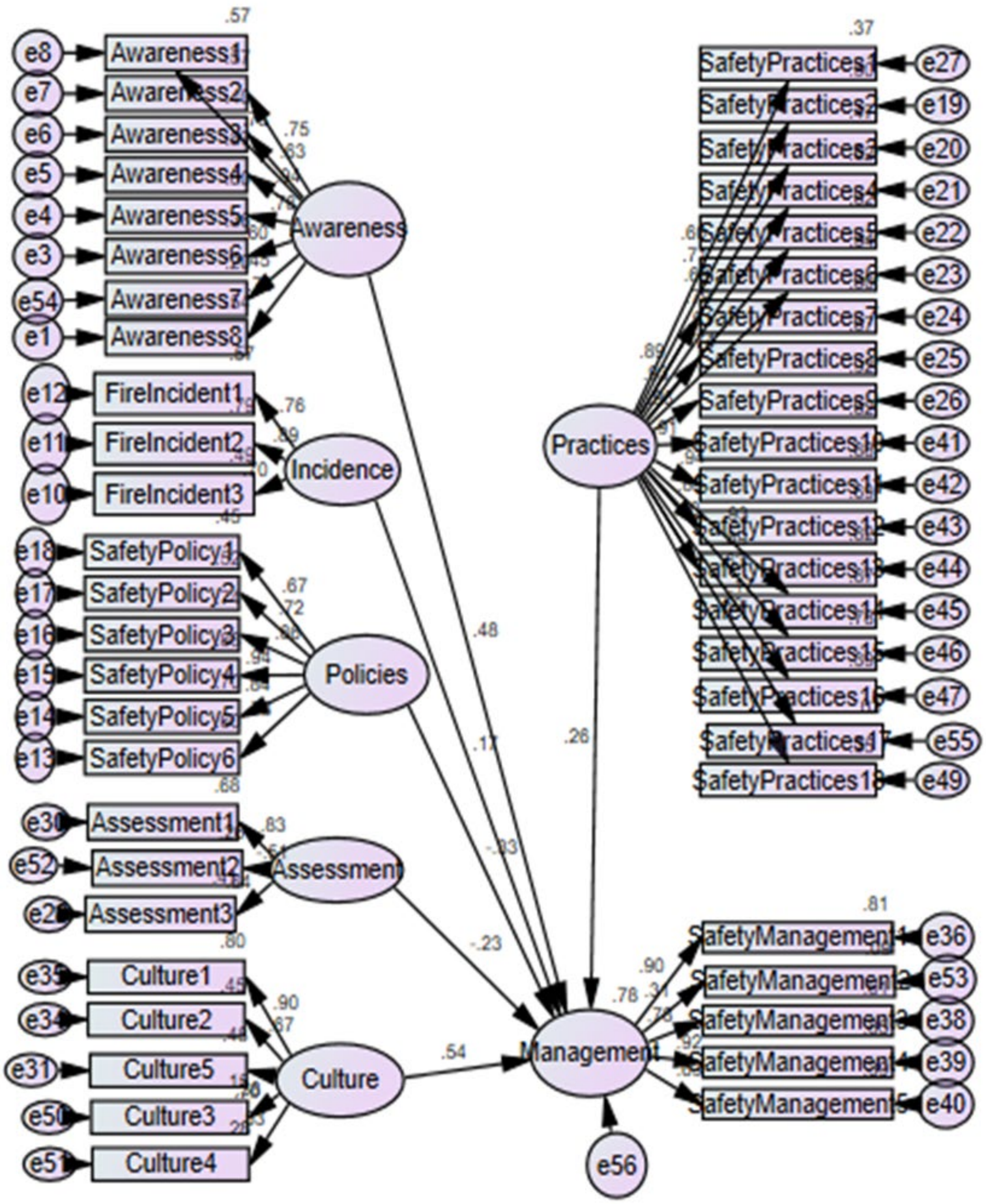


**Figure 1** SEM model for fire safety management of hotels in Nigeria

### *3.1 Worker's Awareness of Fire Safety*

The construct for Fire Awareness has eight variables coded from 1 to 8. Results of the standardized regression weights (SRW) squared multiple correlations (SMC), internal validity, and reliability are presented in Table 3.

**Table 3** Workers' awareness of fire safety

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach alpha |
|---|---|---|---|---|---|---|
| Awareness | Awareness1 | Awareness of fire | 0.739 | 0.546 | 0.000*** | 0.881 |
| | Awareness2 | Fire risk training | 0.817 | 0.668 | 0.000*** | |
| | Awareness3 | Poor housekeeping | 0.689 | 0.475 | 0.000*** | |
| | Awareness4 | Report injuries and hazards | 0.896 | 0.802 | 0.000*** | |
| | Awareness5 | Duties Performance | 0.721 | 0.520 | 0.000*** | |
| | Awareness6 | Fire safety attendance | 0.648 | 0.420 | 0.000*** | |
| | Awareness7 | Risk assessment courses and certifications | 0.505 | 0.255 | 0.000*** | |
| | Awareness8 | Course content of the fire safety | 0.729 | 0.531 | 0.000*** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99% (Kline, 2016; Malhotra, 2020)

The SRWs for the Fire Awareness construct are all high, ranging from 0.896 to 0.505, above the 0.5 minimum thresholds. Consequently, the SMC is also above the average 0.25 lower limits. With a Cronbach alpha of 0.881, above the 0.7 satisfactory level, all the eight variables under the Fire Awareness construct are also statistically significant at a 99 percent confidence level. However, the top Fire Awareness variables are the procedure to report fire hazards and risk training, among other factors. While Fire Awareness seems high among the workers, there is still a chance to improve attendance to risk assessment courses and fire safety training.

The results agree with previous findings that Fire Safety Awareness is a standard measure used in the fire safety management of workers in a hospitality environment (Agbola & Falola, 2021; Hassanain, Aljuhani, Hamida, & Salaheldin, 2022; Kim et al., 2021; Li, Hasemi, Nozoe, & Nagasawa, 2021; Ogochukwu et al., 2019). The results also showed that over 80% of respondents agreed to be conversant with the fire safety awareness in the hotel building. For this reason, efforts are needed to maintain a steady awareness of managing fire protection systems in buildings, and workers should be thoroughly trained and equipped with the fire safety measures and guidelines associated with the hotel premises (Alli, 2008; Hughes & Ferrett, 2011; Wood, 2017).

### *3.2 Causes of Fire Incidents in Hotel Buildings*

The construct Fire Incidence has four variables coded from 1 to 4. Results of the standardized regression weights (SRW), squared multiple correlations (SMC), internal validity, and reliability are presented in Table 4.

**Table 4** Causes of Fire Incidents

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach alpha |
|---|---|---|---|---|---|---|
| Incidents | FireIncident1 | Negligence | 0.764 | 0.584 | 0.001*** | 0.378 |
| | FireIncident2 | Electrical work | 0.893 | 0.798 | 0.000*** | |
| | FireIncident3 | Electrical and mechanical equipment | 0.686 | 0.470 | 0.000*** | |
| | FireIncident4 | Fire-fighting facilities and equipment | 0.057 | 0.003 | 0.022** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99%; **valid at 95% (Kline, 2016; Malhotra, 2020).

The construct's SRWs range from high as 0.893 to as low as 0.057. while three of the constructs are high, above the 0.5 minimum threshold, and one of them was 0.057, below the minimum limit. Consequently, apart from inadequate fire-fighting equipment, the SMC for the other three variables is above the average 0.25 lower limits. With a Cronbach alpha of 0.378, below the 0.7 satisfactory level, only the first three variables under the Fire Incidence construct are also statistically significant at a 99 percent confidence level.

Since Fire Incidence is a negative construct, it could be inferred that most of the fires in hotel premises are caused due to workers' negligence, electrical and mechanical equipment. Hence, the study agreed with previous findings indicating that a significant fire outbreak occurs in hotel buildings due to the occupants' irresponsibility, negligence, violation of construction codes, unawareness of safety measures, carelessness, and lack of training (Amin, Alisjahbana, & Simanjuntak, 2018; Nimlyat et al., 2017; Ogochukwu et al., 2019). However, workers' carelessness, loss of health and safety understanding, and a lack of knowledge and competent staff were major variables that caused the fire, according to another study in Dubai, United Arab Emirates (Adhakari et al., 2020; Tuhul et al., 2021; Zekri, 2013). Perhaps fire dangers are the source of fire, and minimizing them will reduce the number of fire events (Buchanan & Abu, 2017; Jones et al., 2019). Improving the identified variables is desirable and recommended to combat fire incidence in hotels.

### *3.3 Management's Commitment to Policy*

The Fire Safety Policy construct has six variables coded from 1 to 6. Results of the standardized regression weights (SRW) squared multiple correlations (SMC), internal validity, and reliability are presented in Table 5.

**Table 5** Fire Safety Policy

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach Alpha |
|---|---|---|---|---|---|---|
| Policies | SafetyPolicy1 | Fire safety policy | 0.681 | 0.464 | 0.000*** | 0.914 |
| | SafetyPolicy2 | Policy available | 0.728 | 0.529 | 0.000*** | |
| | SafetyPolicy3 | Safety policy reviewed | 0.865 | 0.748 | 0.000*** | |
| | SafetyPolicy4 | Management policy | 0.933 | 0.871 | 0.000*** | |
| | SafetyPolicy5 | Management culture | 0.839 | 0.704 | 0.000*** | |
| | SafetyPolicy6 | Fire Safety training | 0.766 | 0.587 | 0.000*** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99% (Kline, 2016; Malhotra, 2020).

The SRWs for the Fire Safety Policy construct are all high, ranging from 0.933 to 0.681, above the 0.5 minimum threshold. Consequently, the SMC is also above the average 0.25 lower limits. With a Cronbach alpha of 0.914, above the 0.7 satisfactory level, all the six variables under the construct are also statistically significant at a 99 percent confidence level. However, the top Fire Safety Policy variables are the management's adoption of fire hazards identification, safety policy, and the culture of Fire Safety inspections. While responses to Fire Safety Policy seem to be high among the workers, there is still a chance to improve hotel management's general fire safety policy.

The results agree with the findings by Kim et al. (2021), for overall improvements in Fire Safety, especially in high-rise buildings, in line with the British Standard (-8) 9999 policy (Alianto, Nasruddin, & Nugroho, 2022; Brzezinska & Bryant, 2021; Hopkin & Spearpoint, 2021). As hypothesized, each of these dimensions was found to be a significant factor in safety policy, as in management commitment to fire safety, supervisor support, safety communication, safety policies, and safety programs. Also, as predicted, safety policy was significantly related to both safety compliance and safety participation, or worker behaviours. Both safety behaviours were negatively associated with self-reported injury for firefighters not in the "always zero" or no injury group (Smith, 2010; Smith & DeJoy, 2014). According to this theory, investing funds in cascading and implementing safety measures in hotels with safety policies and safety concerns in their strategies makes managers more committed to their roles (Dillette & Ponting, 2021; Pescaroli & Alexander, 2016). According to the finding, fire incidents will have fewer risk factors when organizational safety rules and strategy issues are correctly applied and performed. Therefore, the frequency of fire incidents at work will consequently decrease as a result. Management commitment to fire safety, supervisor support, safety communication, and safety policies and programs. As hypothesized, each of these dimensions was found to be a significant factor in safety policy. Also as predicted, safety policy was significantly related to both safety compliance and safety participation, or worker behaviors. Both categories of safety behaviors were negatively associated with self-reported injury for firefighters not in the "always zero" or no injury group.

### *3.4 Fire Safety Management Practices*

The construct for Fire Safety Practices has eighteen variables coded from 1 to 18. Results of the standardized regression weights (SRW), squared multiple correlations (SMC), internal validity, and reliability are presented in Table 6.

**Table 6** Fire Safety Practices

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach alpha |
|---|---|---|---|---|---|---|
| Practices | SafetyPractices1 | "No Smoking" signs | 0.604 | 0.365 | 0.000*** | 0.957 |
| | SafetyPractices2 | Ventilation outlets | 0.710 | 0.504 | 0.000*** | |
| | SafetyPractices3 | First aid kit | 0.687 | 0.472 | 0.000*** | |
| | SafetyPractices4 | Emergency procedure | 0.787 | 0.619 | 0.000*** | |
| | SafetyPractices5 | Emergency telephone numbers | 0.907 | 0.823 | 0.000*** | |
| | SafetyPractices6 | Assembly (Muster) point | 0.736 | 0.542 | 0.000*** | |
| | SafetyPractices7 | Fire extinguishers | 0.894 | 0.799 | 0.000*** | |
| | SafetyPractices8 | Service/maintenance | 0.932 | 0.870 | 0.000*** | |
| | SafetyPractices9 | Debris and damage | 0.959 | 0.920 | 0.000*** | |
| | SafetyPractices10 | Unobstructed access | 0.906 | 0.820 | 0.000*** | |
| | SafetyPractices11 | Padlocks keys and others | 0.936 | 0.876 | 0.000*** | |
| | SafetyPractices12 | Emergency exit training | 0.830 | 0.876 | 0.000*** | |
| | SafetyPractices13 | Adequate PowerPoint | 0.903 | 0.815 | 0.000*** | |
| | SafetyPractices14 | Switches/ PowerPoint | 0.934 | 0.872 | 0.000*** | |
| | SafetyPractices15 | Breaker switches | 0.886 | 0.785 | 0.000*** | |
| | SafetyPractices16 | Suitable fire extinguishers | 0.626 | 0.392 | 0.000*** | |
| | SafetyPractices17 | Electrical units and cables | 0.163 | 0.027 | 0.562 | |
| | SafetyPractices18 | Procedure in place | 0.592 | 0.351 | 0.000*** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99% (Kline, 2016; Malhotra, 2020).

The SRWs for the Fire Safety Practices construct are high, ranging from 0.936 to 0.592, above the 0.5 minimum threshold, except the care for Electrical units and cables, which has 0.163, below the minimum acceptable level. Consequently, most of the SMC is also above the average 0.25 lower limits, except for the care for Electrical units and cables. With a Cronbach alpha of 0.957, above the 0.7 satisfactory level, seventeen of the eighteen variables under the construct are also statistically significant at a 99 percent confidence level. Consequently, the top Fire Safety Practices variables are the compartmentalization of spaces by locks, appropriate placement of control switches, and the culture of regular equipment maintenance and servicing. While most of the responses for Fire Safety Practices seem to be high among the workers, there is still the chance to improve the quality of electrical units and cables to effectively check fire in hotel environments.

The results align with the International Fire Safety Standard Common Principles (IFSS-CP) that fire safety practices enhance public confidence in line with the United Nations' sustainability goals (Hassanain, Al-Harogi, et al., 2022; Ivanov, Chow, Yue, Tsang, & Peng, 2022; Roslan & Said, 2017). According to the finding, most hotels have fire sprinklers, emergency exits, assembly (Muster) points, emergency procedures, and telephone numbers; suitable fire extinguishers are in place, and associated pumps are in good shape and up-to-date. However, implementing quality safety practices in the hotel can boost and enhance the hotel's prestige, thereby limiting the extra cost spent on fire incidents/accidents (Gstaettner et al., 2019; Ogetii, 2019).

### *3.5 Fire Incidence in Hotel Buildings*

The Assessment of Fire Incidents constructs three variables coded from 1 to 3. Results of the standardized regression weights (SRW) squared multiple correlations (SMC), internal validity, and reliability are presented in Table 7.

**Table 7** Assessment of Fire Incidents

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach Alpha |
|---|---|---|---|---|---|---|
| Assessment | Assessment1 | Major fire incidents | 0.828 | 0.686 | 0.001*** | 0.015 |
| | Assessment2 | Minor fire incidents | 0.529 | 0.280 | 0.006*** | |
| | Assessment3 | Injury and loss of life | 0.624 | 0.390 | 0.001*** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99% (Kline, 2016; Malhotra, 2020).

The SRWs for the Assessment of a Fire Incidents construct are high, ranging from 0.828 to 0.529, above the 0.5 minimum threshold. Consequently, the SMCs are also above the average 0.25 lower limits for construct acceptability. With a Cronbach alpha of 0.015, below the 0.7 satisfactory level, all three variables under the construct are also statistically significant at a 99 percent confidence level.

Consequently, they reported that most hotel fire incidents were major ones that resulted in severe injuries or even loss of life. Therefore, employers and workers must adhere to prescribed fire safety practices and techniques that decrease the danger and impact of fire (Ivanov et al., 2022; Shariff, Yong, Salleh, & Siow, 2019; Sun & Luo, 2014). It is recommended that a customized fire safety strategy should be created and implemented right at the planning and design stages before building work is completed to achieve the recommended control systems for fire safety (Navitas, 2014; Poliakova & Grigoryan, 2018).

### *3.6 Culture and Hotel Fire*

The construct for Culture and Fire has five variables coded from 1 to 5. Results of the standardized regression weights (SRW) squared multiple correlations (SMC), internal validity and reliability are presented in Table 8.

**Table 8** Culture and Fire

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach Alpha |
|---|---|---|---|---|---|---|
| Culture | Culture1 | Cultural practice | 0.794 | 0.630 | 0.000*** | 0.791 |
| | Culture2 | People's cultures | 0.662 | 0.438 | 0.000*** | |
| | Culture3 | Relationships | 0.502 | 0.252 | 0.234 | |
| | Culture4 | Sustainability of hotel | 0.604 | 0.365 | 0.004*** | |
| | Culture5 | Workers' and staff culture | 0.761 | 0.365 | 0.000*** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99% (Kline, 2016; Malhotra, 2020).

The SRWs for Culture and Fire construct are all high, ranging from 0.794 to 0.502, above the 0.5 minimum thresholds. Consequently, the SMCs are also above the average 0.25 lower limits. With a Cronbach alpha of 0.791, above the 0.7 satisfactory level, four of the five variables under the construct are statistically significant at a 99 percent confidence level, with one falling below the minimum threshold.

While the people recognize culture as one of the indices for fire control, their responses show that it does not promote fire danger in hotels. Though it may not be applicable in the study area, previous studies indicate that a people's culture affects fire safety, especially during emergency evacuations (Agbola & Falola, 2021; Alianto et al., 2022; Amin et al., 2018; Cvetković et al., 2022; Ivanov et al., 2022). Furthermore, cultural practice is one of the contributing factors to fire incidents and can negatively influence the sustainability of the hotel if it is not adequately addressed and implemented.

### *3.7 Fire Safety Management*

The construct for Culture and Fire has five variables coded from 1 to 5. Results of the standardized regression weights (SRW), squared multiple correlations (SMC), internal validity, and reliability are presented in Table 9.

**Table 9** Hotel's Fire Safety Management

| Construct | Code | Variable | SRW | SMC | Validity | Cronbach Alpha |
|---|---|---|---|---|---|---|
| Management | SafetyManagement1 | Awareness of fire safety | 0.876 | 0.767 | 0.001*** | 0.778 |
| | SafetyManagement2 | Safety policy and standards | 0.298 | 0.089 | 0.047** | |
| | SafetyManagement3 | Good fire safety management | 0.755 | 0.570 | 0.000*** | |
| | SafetyManagement4 | Fire Safety practices | 0.942 | 0.888 | 0.000*** | |
| | SafetyManagement5 | Adequate spacing | 0.559 | 0.313 | 0.005*** | |

Note: SRW > 0.5; SMC > 0.25; Cronbach alpha > 0.7; ***valid at 99%; **valid at 95%; (Kline, 2016; Malhotra, 2020).

Four SRWs for Fire Safety Management construct are high, ranging from 0.942 to 0.559, above the 0.5 minimum threshold. Consequently, their SMCs are also above the average 0.25 lower limits. With a Cronbach alpha of 0.778, above the 0.7 satisfactory level, four of the five variables under the construct are statistically significant at a 99 percent confidence level, the other at 95 percent.

While people recognize awareness, culture, and safety practices as the major indices for fire control, there is a need to improve safety policy and standards, which according to scholars, can enhance fire Safety Management in hotels (Ebekozien, Aigbavboa, Ayo-Odifiri, & Salim, 2020; Hassanain, Aljuhani, et al., 2022; Kim et al., 2021; Ouache, Nahiduzzaman, Hewage, & Sadiq, 2021; Wang et al., 2021). It could be seen that the most negligible value is the relationship between evaluation and control of fire safety using policy, information, standards, and fire safety management tools in the hotel, with the least SRW of 0.0298 due to the low level of agreement by respondents. However, good fire safety management could minimize the risk of the fire incident and enhance fire incident management, thereby establishing a high standard of reliability for the hotel in terms of safety measures. It should be "stakeholder duty" to provide and maintain an appropriate level of fire safety management, and the best way to do this is through enhanced training, inspection, auditing, and information. Where quantitative risk assessment is performed, reliable data are essential to the management function. The investigation identified a vulnerability in this area, which management has in various ways acknowledged. Adequate fire safety management is crucial for public safety, which is why organizations that often use a complete quality management approach have found it more straightforward to accept safety elements (Buchanan & Abu, 2017; Samson & Terziovski, 1999).

### *3.8 Framework for Hotel Fire Management*

The high frequencies and death rates of fires in Nigeria call for concerted efforts to tackle the fire problem. The volatile salutation of Port-Harcourt as a city in an oil-producing state makes it prone to fire disasters in hotels, among other high-rise institutions. Three main factors were considered in the study of hotel fires in Port-Harcourt: human, material and standards.

While the human factors included the people's culture and their awareness of fire dangers in hotel premises, the material aspects have to do with the extent of fire due to mechanical, electrical among other tangible elements. Policy and standards entail regulated strategies and practices of the management and workers regarding fire safety. The framework, as presented in Figure 2, is based on novel findings, providing a basis for further research in the fire safety management of hotels in Nigeria.

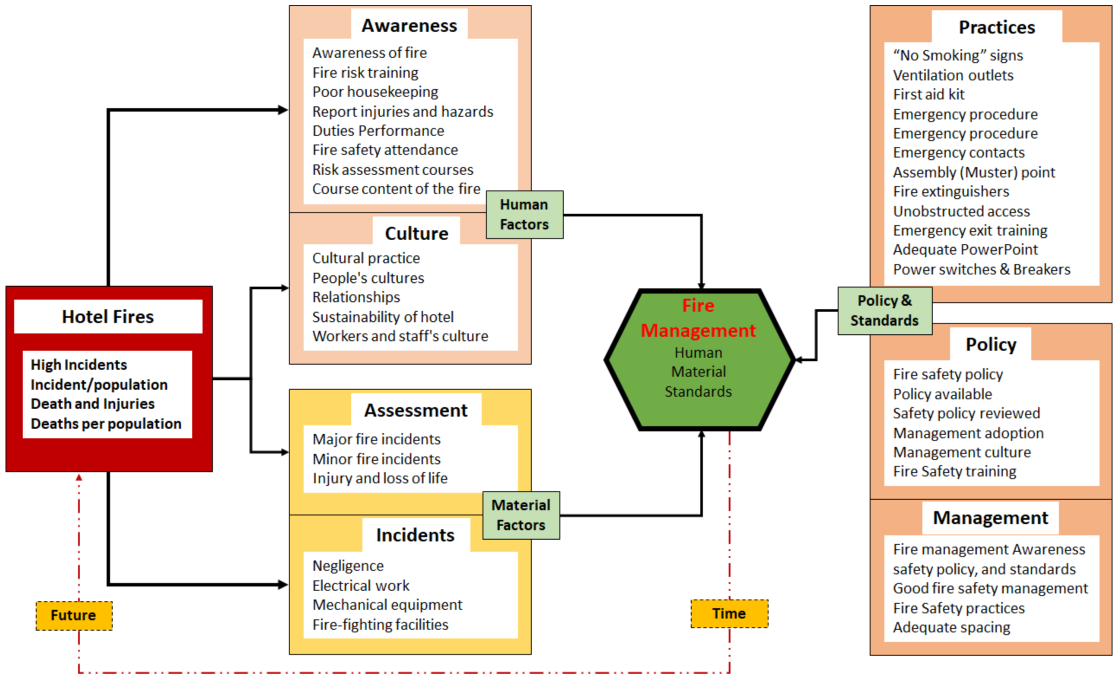


**Figure 2** Framework for Hotel Fire Management in Nigeria

## 4. Conclusion

Though Nigeria does not occupy the top rank of countries in most frequent fire disasters in the world, it ranks among the top countries with a high number of deaths per 100 fire incidents. Furthermore, Nigeria, with an average fire incident of 56 spread among the 36 states and the FCT, Port-Harcourt has higher chances of fire due to high population and oil exploration activities. Hotels, as places of relaxation and leisure, need to be safe and secure from threats of fire disasters. While the level of Fire Awareness seems to be high among the workers, there is still a chance to improve attendance to fire safety training. On their part, hotel management should improve the general fire safety policy among workers and the environment. From the responses, it could be established that most hotel fire incidents were major ones that resulted in severe injuries and loss of life.

Consequently, most fire incidents in hotel premises are caused due to workers' negligence and electrical and mechanical equipment defects. To this end, there is a need to improve the quality of mechanical units and electrical cables to effectively check fire occurrences in hotel environments. While the people recognize culture as one of the indices for fire control, their responses show that it does not promote the danger of hotel fire in Port-Harcourt - Nigeria.

While the respondents recognize awareness, culture, and safety practices as the major indices for fire control, there is a need to improve safety policy and standards, which according to scholars, can enhance fire Safety Management in hotels. It could be seen that the most negligible value is the relationship between evaluation and control of fire safety using policy, information, standards, and fire safety management tools in the hotel. Therefore, employers and workers must adhere to prescribed fire safety practices and techniques that decrease the danger and impact of fire. Right at the planning stage, a customized fire safety strategy should be created and implemented before building work is completed to achieve the recommended control systems for fire safety. Therefore, this study's findings are essential to hotel entrepreneurs, managers, fire safety experts, and building designers.

## Conflict of Interest

The authors declare that there is no conflict of interest in this study. Materials from other sources are cited as much as possible. Authors appreciate contributions from their respective institutions, especially research assistants and respondents.

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# Towards Achieving Sustainable Development Goal-2030 Agenda-Thirteen: A Review of Technological Advances from the Built Environment Professionals

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## ABSTRACT

Natural resources are increasingly under pressures to cater for the growing human population and their corresponding, often conflicting needs. However, the need to conservatively utilize these resources without deteriorating the environment to the disadvantage of the future generations has prompted some actionable steps at the global level, the prominent of which is the promulgation of the United Nation's Sustainable Development Goal 2030 (SDG-2030) Agenda, having seventeen (17) inter-related actionable areas of human endeavours (i.e., Agenda). Of particular interest within this context is the Agenda Thirteen (Agenda-13) which encompasses the need for urgent action to combat Climate Change and its impacts across various areas of human engagements. This is necessary as Climate Change impacts are characterized with anthropogenic carbon emissions resulting in global temperature rise, sea level rise, flooding, desertification, droughts, and other related disasters. Within the precinct of Built Environment, it is established that building construction and operation alone account for about 40% of the global emissions. This calls for concerns and requires urgent collaborative actions to curtail the trend. This submission, which is review based therefore, highlights various joint efforts particularly, integration of technological advancements by the relevant building professionals, towards attaining the goal of Agenda-13. This is with a view to limiting climate change enablers for reduced environmental impacts. These collaborative efforts are categorized into *pre-construction* and *post-construction* activities from the relevant professionals in the built environment. While the former includes Indoor Thermal Comfort Simulation, Integration of Daylighting Technologies, and adoption of Computational Fluid Dynamics integrated architectural design process, the latter consists of design of Double Skin Facades, development of Building Integrated Photovoltaics façade, integration of Evacuated Tube Solar Air Collector System, adoption of Phase Change Material on Building façade, and implementation of Life Cycle Energy Analysis Policy, among others. These endeavours aim at reducing carbon emissions at the building micro level for overall clean, safe and sustainable global environment.

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## 1. Introduction

Rapid growth in population, economic activities and general urbanization during the last decades have had several environmental, economic, and social consequences, as governments across the globe attempt to improve the wellbeing of the teeming population Anukwonke et al., 2022; Koukelli, Hoces, and Asut, 2021). In effect, natural resources are transformed to build more houses, schools, hospitals, roads, railways, bridges, public libraries, and other public facilities, to accommodate the needs of the growing population. Thus, increase in industrial production gave rise to consumerism, with its attendant massive pressure on natural resources and the environment, leading to the undermining of the nature balance (Blewitt, 2014). This has raised concerns on depletion of local natural resources over the years, and signaled negative impacts capable of harming the well-being of the future generations on a global scale. Consequently, future severity of the problem has necessitated the need to embark on ecological and environmental preservation, for Sustainable Development of the natural resources (Stanujkic et al., 2020).

Thus, Sustainable Development within this context defines the process of transformation of natural resources without degradation for further utilization by future generations (Cohen, 2017). It connotes the use of natural resources without depleting them beyond replenishment, and without deteriorating the environment where they are situated (Yu et al., 2020). The term Sustainability which was initially introduced to represent a connection between development and environment, has become broader to include all aspects of development, inclusive of economic, social, and environmental dimensions, as the goals of sustainable development are now expanded, relative to those initially conceived in the 1990s (Rogers, Jalal and Boyd, 2012).

Arising from the foregoing, the need for Sustainable Development led to series of efforts at the international level which informed convergence of the maiden global conference in Brazil, the Earth Summit in 1992 (i.e., Rio-de-Janeiro-92), and a follow-up conference twenty years later (2012) in the same country (i.e., Rio+20), among others. These were followed with the declaration of Millennium Development Goals (i.e., MDG-2015) by the United Nations in 2015 (United Nations, 2015). Having observed unrealizable nature of the MDG-2015 Agenda, it was replaced with a more robust framework tagged, Sustainable Development Goals (SDG) with its main focus in 2030 (i.e., SDG-2030) (Stanujkic and Karabaševic, 2018; Attoye and Hassan, 2017; Nejat et al, 2015). This new concept is composed of seventeen (17) comprehensive objectives, 169 targets, separate ways of executions, and follow up actions. The seventeen (17) objectives are serially tagged Goals 1 to 17, having 'Poverty Elimination' and 'Partnership for goals' as Goals 1 and 17 respectively. Of primary interest for the purpose of this submission is Goal 13 (i.e., Agenda 13) with the focus on 'the need for urgent action to combat Climate Change and its impacts'. This is to be considered within the confine of the Built Environment (as against Natural Environment).

Built Environment constitutes the human-made surroundings that provide the setting for human activities, ranging in scale from buildings and parks or green space to neighborhoods and cities, often inclusive of their supporting infrastructure (Kaklauskas and Gudauskas, 2016). It encompasses the places where we live and work and the ways we travel (Thompson, and Kent, 2017). Buildings account for approximately 40% of global energy consumption (Attoye and Hassan, 2017; Nejat et al, 2015) as the built environment contributes significantly to global greenhouse gas emissions. Over 15% of carbon emissions result from energy consumption by buildings in many industrialised nations (Nejat et al, 2015; Gillott, and Spataru, 2010). Despite the level of emissions, the global building stock is expected to increase and double by 2060 because of new constructions, particularly in developing countries, due to the rapid growth in population, economic activities and fast urbanization, with an attendant increase in $CO_2$ emissions (Lotfabadi, 2013). Climate change, caused by the escalating levels of greenhouse gases in the atmosphere is therefore posing threats to human progress and well-being. Global climate disruption poses the most significant defiance to the environmental security of the earth and the heritage for future generations (Jafari, 2013; World Bank, 2016). Thus, there is the need for sustainable utilization of the available limited resources to guarantee safety of the future generations (Anukwonke et al., 2022). In line with the Agenda Thirteen of the United Nation's Sustainable Development Goal (SDG Agenda-2030), this paper therefore contributes to the existing body of knowledge by examining some of the efforts to combat Climate Change and its impacts, within the precinct of the Built Environment. This is with a view to reducing global carbon emissions and minimizing building construction impacts, for overall clean, safe and sustainable global environment.

## 2. Literature Review

Climate change is considered one of the severe issues that threaten sustainable development with regard to the environment, human health, food security, economic activities, natural resources and infrastructure (Karimi et al., 2022). It refers to climate fluctuations, directly and indirectly, related to human activities and change in the atmospheric composition (Amos et al. 2015). Recent scientific evidence shows impacts of climate change in form of the frequency, intensity and duration of extreme weather events, such as changing rainfall patterns, rising temperatures, droughts, among others (Table 1). These would remain unabated unless practical measures are taken to reduce greenhouse gas emissions, and mitigate climate change risks (Majedul Islam, 2022; Bell et al. 2018; Aphunu and Nwabeze 2012). Average global surface temperature has been rising in the last century as Intergovernmental Panel on Climate Change (IPCC) observed that the average of 0.87 °C (0.75–0.99 °C) for the 2006–2015 decade was over the second half of the nineteenth-century average (Laurini 2019; Capellán-Pérez et al. 2016). A future projection indicates that an average temperature increase of 1.5 °C may be realised as soon as 2026, and the global average temperature rise of between 2.7 and 5.2 °C above pre-industrial levels by 2100 (IPCC 2018; Foster et al. 2017; Capellán-Pérez et al. 2016; United Nations, 2015).

**Table 1** Impact of climate change and extreme events on humanity

| Climatic factors | Exposure pathways | Impact on humanity |
|---|---|---|
| • **Increasing temperatures Extreme heat events** | • Extreme heat, worsened air quality | • Increase in heat-related illness and death<br>Elevated risk of cardiovascular and respiratory illnesses and death |
| • **Rising sea-level Frequent and intense extreme precipitation, cyclones, hurricanes and storm surges and associated flooding** | • Contaminated water; salinity intrusion; disruption of houses and other infrastructures | • Increased waterborne diseases; Reduced agricultural production; Injuries; Drowning; Preterm birth and low birth weight<br>Infrastructure disruptions and post-event disease spread; Negative impact of mental health and well-being |
| • **Change in temperature extremes and seasonal weather pattern** | • Change in infectious agents | • Increased vector-borne diseases |
| • **Change in precipitation pattern and run-off** | • Recreational water and shellfish contaminated with waterborne pathogens | • Increased water and foodborne diseases |
| • **Droughts** | • Reduced water quantity<br>Reduced air quality | • Reduced agricultural production; Respiratory impacts related to reduced air quality; Mental health impacts |
| • **Wildfires** | • Rising temperatures and hotter, drier summers increase the frequency and intensity of wildfires | • Smoke inhalation; Burns and other traumatic injuries<br>Asthma exacerbations<br>Mental health impacts |

(Source: Majedul Islam, 2022)

Climate Change is considered as the alteration in the climatic arrangements over long periods arising from the natural processes like variability in sun radiations, volcanic eruptions, modifications in the climate system or because of the activities by humans' pollution, industrialization and land use changes (Hughes et al. 2018). However, extensive scientific analysis, most climate science and the Fourth Assessment Report of the IPCC agree that anthropogenic activities have had an increasingly dominant impact on the observed global warming since the mid-twentieth century (Malla et al., 2022; IPCC 2018). Human activities are observed to be the primary sources of excessive greenhouse gases (GHGs). Increasing emission of these GHGs inclusive of CFCs (chlorofluorocarbons), HCFCs (hydrochlorofluorocarbons), HFCs (hydrofluorocarbons), PFCs (perfluorocarbons), and SF6 (Sulphur hexafluoride) results in heat-trapping phenomenon which reduces heat loss into outer space, thereby making the universe hotter than expected, a scenario referred to as 'the greenhouse effect' (Farooqi et al., 2022; Anukwonke et al., 2022).

The built environment has a strong impact on both human and environmental health as development of buildings and other infrastructure within, consume great quantities of materials and energy during construction, operations, and eventual deconstruction at the end of their life cycles (Bardage, 2017). With increasing global population, urbanization and general economic activities during the last decades, there has been a corresponding increase in the pressure exerted on the available resources. These have raised concerns over depletion of local natural resources and supply difficulties as the building sector constitutes one of the major end users of energy (Koukelli, Hoces, and Asut, 2021; Kwong, Adam, and Sahari, 2014). Buildings account for about 15 % of carbon emissions, with transport and industry being responsible for 14 % and 21 %, respectively, and the remainder is due to other activities (Karyono and Bachtiar, 2017). Thus, efficient and sustainable utilization of energy is essential in conserving the fast-depleting resources, and protecting the environment from avoidable carbon emissions.

From the foregoing, needs to address climate change has featured in the policy frameworks of many countries (Valizadeh et al. 2020; Karimi et al. 2018). The threat of climate change has become a problem of the global commons which has brought the international community together, to devise mechanisms for addressing it particularly, to keep the global warming below 2 °C (Indukuri, 2022). The United Nations serves as an umbrella organisation with its key institutions at the forefront of propelling climate action from the 1970s. With the Stockholm Conference of 1972 to address global environmental issues, formation of the United Nations Environment Programme (UNEP) was achieved. Vienna Convention of 1985 brought attention to the protection of the ozone layer and made way for the Montreal Protocol of 1987 that set limits on the use and production of ozone depleting substances. With emerging consciousness and awareness on climate change, IPCC was established in 1988, to provide scientific information on the impacts, hazards and risks of climate change, with indications for the possible responses to deal with it. With the Earth Summit of 1992, a framework convention (United Nations Framework Convention on Climate Change i.e., UNFCC) was adopted to formulate principles, general goals and actions that countries should take as precautionary measures to limit GHG emissions. So far, not fewer than 197 member countries have ratified the UNFCCC, and are party to it. Hence, a Conference of Parties (COP) is held every year, and since inception, a total of twenty five (25) had been held (as at 2019) (Indukuri, 2022; Attoye and Hassan, 2017). The Earth Summit of 1992 was followed with series of other conventions: in Johannesburg (2002), the provisions of Earth Summit of 1992 were renewed; in Rio de Janeiro (2012), the idea of sustainable development in the context of economic and sociocultural settings, in addition to the environmental dimension was promoted; earlier, in the year 2000, an eight-point agenda, 'Millennium Development Goals' (MDGs-2015 Agenda) was promoted. Having measured its success for a period of fifteen (15) years, MDGs-2015 Agenda was replaced by another fifteen-year Programme, Sustainable Development Goals (SDG – 2030 Agenda) in Paris, 2015. The main agenda of SDGs-2030 are poverty elimination, provision of favourable and decent living conditions for people all over the globe by ensuring world peace, and sustainable economic and social development. The new Agenda is composed of 17 comprehensive objectives (known as SDGs), 169 targets, separate ways of executions, and follow up actions. Of the seventeen (17) goals, the first one, Goal 1, addresses 'Poverty eradication' as the last one, Goal 17, emphasises 'Partnership for goals' (Yu et al., 2020). Within the context of Built Environment, the focus of this submission is the Goal 13, which encompasses the need for urgent action to combat Climate Change and its impacts on the tropical design. The tropical climate is mainly characterized by an elevated temperature, the basis of which indoor thermal discomfort is usually experienced. To achieve comfortable indoor thermal environment, adoption of active measures such as installation of air-conditioners is usually integrated with the consequential increase in the resulting carbon emissions. As a departure from the old approach, this submission reviews some of the advances from the professionals in the Built Environment (i.e., Architects, Planners, Engineers, etc.) in their approach to combat Climate Change through reduced carbon emissions. Thus, subsequent sections of this submission dwell on the individual/joint efforts being made by the relevant professionals in the built environment (i.e., Architects, Planners, Engineers, etc.) towards achieving this important Goal-13 of the SDG-2030 Agenda.

## 3. Methodology

This submission adopts a literature review approach with focus on attainment of indoor thermal comfort particularly, in the tropical design through multi-disciplinary deployment of technological advancements from related professionals in the built environment inclusive of Architects, Planners, Engineers, etc. The approach is categorized into pre-construction and post-construction technological advancements, as highlighted in the following sections.

### *3.1 Pre-Construction Technological Advancements*

In an attempt to reduce carbon emissions from building design and construction, evaluations of building performance are done by determining its potential carbon emissions at its design stage, ahead of actual construction. This is done through exploration of possible design options with a view to determining and adopting most efficient, and economical building design, for reduced carbon emission upon its construction, and subsequent usage. These pre-design evaluations usually involve building simulations that cover diverse areas of building performance for an overall efficient building energy consumption.

Building simulation involves subjecting virtual building models into performance analysis using appropriate software. It is a powerful tool that architects, planners, engineers, and other relevant professionals use to analyze how the form, size, orientation, and type of building systems affect energy performance of the building. Considering building input parameters, it is used to optimise building energy efficiency for informed design decisions (to improve building energy performance) with regard to the buildng envelope, glazing, lighting, HVAC, etc. (Olaniyan, Soyebo and Oyadokun, 2018). As a modern design tool, this analysis is particularly useful to attain best design solutions in the early phases of a project design in diverse areas of building performance inclusive of Indoor Thermal Comfort, Daylighting, Computational Fluid Dynamics, and Life Cycle Analysis, among others (Energy Design Resources, 2021). Each of these diverse areas is considered in turn, with specific applications by previous researchers, to demonstrate their practical influence on overall reduced carbon emissions:

#### 3.1.1 Indoor Thermal Comfort Simulation

In order to respond to the climate change challenges, in an attempt to achieve sustainable design solutions, thermal simulation programs are employed to analyse thermal and energy behaviours of a building. This to arrive at specific thermal targets especially indoor thermal environment, through reduction of energy consumption with attendant environmental impacts (Olaniyan et al, 2018; Wang, Yan and Yi, 2011). Thermal comfort defines the state of mind that expresses mental satisfaction with the surrounding thermal environment (Shastrya, Mania and Tenoriob, 2016). It is regulated by balanced combination of environmental parameters (i.e., ambient temperature, mean radiant temperature, water vapour pressure or relative humidity, and relative air velocity), and personal parameters (i.e., clothing or thermal resistance, and activity or metabolic rate). The primary aim is to ensure adequate thermal capacity is available in the building structure and interior envelope surfaces of habitable rooms for overall thermal comfort of the occupants (Prianto and Depecker, 2003). Ordinarily, this is attained through the use of active measures such as air-conditioning systems with its attendant carbon emissions, arising from fossil fuel that powers the system. However, with deployment of technological advancement through pre-construction numerical simulation of the proposed structure(s), to analyse the influence of design elements and building envelopes on indoor thermal comfort for sustainable building development, best design solutions are easily obatained with pre-determined minimal carbon emissions (Energy Design Resources, 2021). A typical illustration of a virtual building model subjecting to such a simulation environment (i.e. DesignBuilder) is demonstrated in Figure 1, with some thermal comfort data output shown in Figure 2.

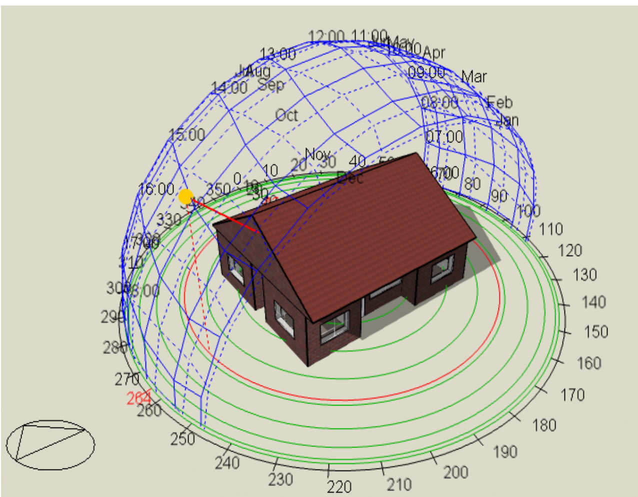



**Figure 1** Typical Virtual Model of the Building as displayed on DesignBuilder software Interface (Source: Author's work, 2022)

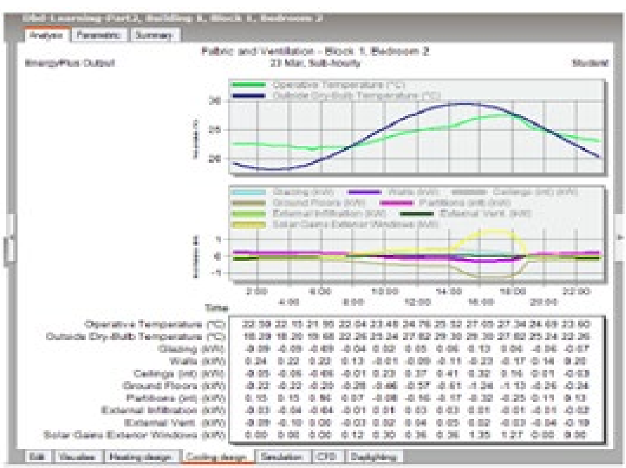


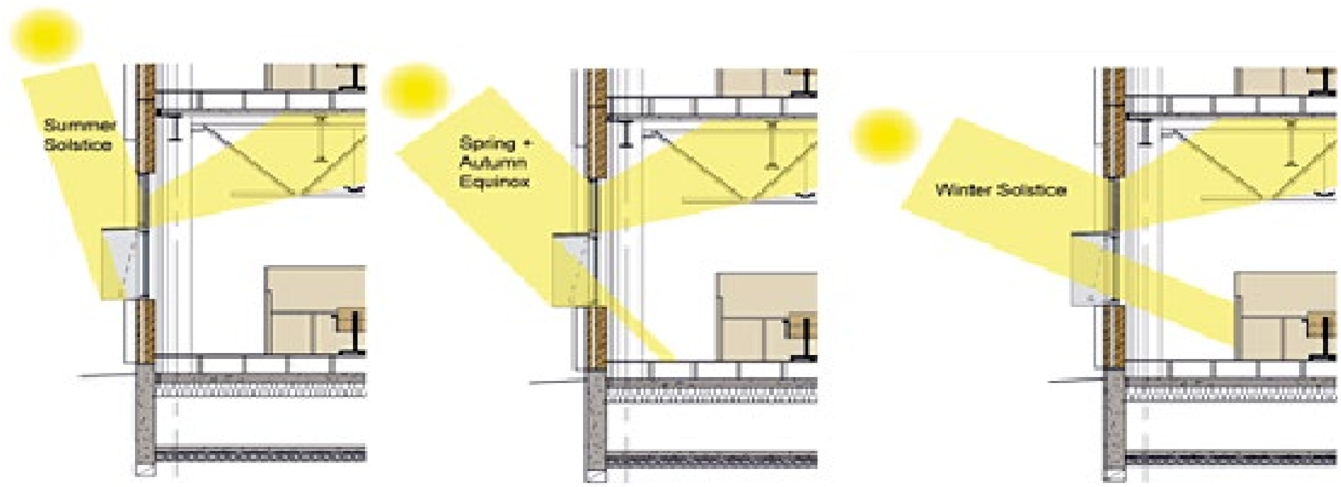
**Figure 2** Typical thermal comfort data output for indoor Thermal Comfort for a Residential apartment (Source: Author's work, 2022)

In effect, carbon emissions are reduced with a view to combating climate change impacts, in line with SDG-2030 Agenda 13. Such simulation software may include Anthermc, DesignBuilder, eQUEST, TRACE 700, IES, TAS, TRNSYS, COMFIE, etc., (BEST Directory, 2022; Olaniyan, 2018). Typical illustrations abound in previous research works where significant evidence-based reduction in carbon emissions were achieved to arrive at energy efficient building designs. These include: building's energy performance and indoor thermal comfort for a hot and semi-arid climate by El-Bichri et al (2022): dynamic thermal simulation of five ecological houses located in different cities of France with different climate zones by Kaoula and Bouchair (2020); experimental validation of five house-like cubicles, built at a real scale in a village with a typical Mediterranean climate located in Spain, under summer conditions by Serrano et al. (2016); experimental testing of five earth brick types in a laboratory wall prototypes by Bruno et al. (2020); several studies comparing thermal implications and energy optimisation between various walling materials (Homod et al., 2021; Marincic et al., 2014; Patel & Prasad, 2016; Sghiouri et al., 2020; Taylor et al., 2008), among others. In each of these cases, building thermal performance simulation through application of technological advancement was carried out to optimise energy efficiency of the building, resulting in reduced energy consumption with the overall reduction in carbon emissions

### 3.1.2 Integration of Daylighting Technologies

Daylighting is a renewable energy solution for illumination and visual comfort in buildings (Yu, Su and Chen, 2014). It is regarded as a basic energy saving design strategy for buildings (Ihm, Nemri and Krarti, 2009). It defines controlled admission of natural light, direct sunlight, and diffused-skylight into a building to reduce electric lighting with a view to saving energy (Ander, 2016). It involves redirection of sunlight into building spaces to maximise sufficiently, usage of natural lighting for reduced electric lighting (Alva & Madamopoulos, 2020). It is an energy-efficient strategy that integrates many technologies with design philosophies. The potential energy saving through daylighting is mainly achieved by applying daylight-linked artificial lighting control system, which regulates artificial lighting output in accordance with the quantity of daylighting that penetrates through the existing windows or other relevant openings, to ensure that the required indoor illuminance level is maintained. In this regard, both High frequency dimming control, and on-off control, are the two commonly adopted lighting control system in day-lit buildings (Li, 2010). Apart from the basic daylight apertures (i.e. windows and passive skylights), advanced daylighting technologies comprises of an integrated daylight-responsive control system involving one or more of: Climate-responsive window-to-wall area ratio; High-performance glazing; Daylighting-optimized fenestration design; Skylights (active); Tubular daylight devices; Daylight redirection devices (Figure 3); Solar shading devices; Daylight-responsive electric lighting controls, etc.

Ordinarily, artificial lighting facilitates heat gain inside the building. However, reduction in the use of artificial lighting through integration of daylighting technologies with proper electric lighting control system, can result into considerable less cooling load and potential for smaller cooling, ventilation and air-conditioning (HVAC) plants, since most of non-domestic buildings are in use during daylight hours (Li, Lam and Wong, 2006). Thus, potential energy savings from artificial lighting through daylighting technologies can be determined using European Standard EN15193, static climate-based Daylight Factor (DF) method, dynamic climate-based Daylight Coefficient (DC) method, among others. Using Computational analysis, daylighting room performance can be obtained through lighting simulation tools such as Raytracing, Energyplus, Relux, Daysim, TAS, etc (Yu, Su and Chen, 2014). From previous studies, energy consumption savings from electric lighting in non-domestic buildings of: 20–30%, and 25-40% in Hong Kong and USA respectively, were recorded (Li and Wong, 2007); 20–40% reduction in another studies by Embrechts and Bellegem (1997); 10.8 to 44% reductions in UK buildings by Ghisi and Tiker (2006); 30 to 77% reductions in field measurements and computer simulation analysis on commercial buildings from studies by Doulos, Tsangrassoulis and Topalis (2008). As part of daylight harvesting strategies, Kontadakis et al. (2018) demonstrate adoption of interior and exterior light shelf, as a component of the building façade; Lee et al. (2018) illustrate light-redirecting performance of an awning system (with a built-in light-shelf) with its energy saving-capability; use of anidolic reflector (i.e. light pipe) in the ceiling plenum was studied by Kennedy and O'Rourke (2015), and; light redirecting system through reflective louvers, Okasolar in-pane louver series was developed by Okalux (Okasolar, 2018), to demonstrate its energy saving capabilities. These daylighting strategies illustrate a global shift towards more efficient energy resource management, with its end-use lower energy consumption and attendant reduced carbon footprint potentialities.




(a) (b) (c)

**Figure 3** Seasonal performance of shading, redirection devices for optimised daylighting during: (a) Summer Solstice (b) Spring and Autumn Equinoxes; (c) Winter Solstice (Source: Ander, 2016)

Ordinarily, artificial lighting facilitates heat gain inside the building. However, reduction in the use of artificial lighting through integration of daylighting technologies with proper electric lighting control system, can result into considerable less cooling load and potential for smaller cooling, ventilation and air-conditioning (HVAC) plants, since most of non-domestic buildings are in use during daylight hours (Li, Lam and Wong, 2006). Thus, potential energy savings from artificial lighting through daylighting technologies can be determined using European Standard EN15193, static climate-based Daylight Factor (DF) method, dynamic climate-based Daylight Coefficient (DC) method, among others. Using Computational analysis, daylighting room performance can be obtained through lighting simulation tools such as Raytracing, Energyplus, Relux, Daysim, TAS, etc (Yu, Su and Chen, 2014). From previous studies, energy consumption savings from electric lighting in non-domestic buildings of: 20–30%, and 25-40% in Hong Kong and USA respectively, were recorded (Li and Wong, 2007); 20–40% reduction in another studies by Embrechts and Bellegem (1997); 10.8 to 44% reductions in UK buildings by Ghisi and Tiker (2006); 30 to 77% reductions in field measurements and computer simulation analysis on commercial buildings from studies by Doulos, Tsangrassoulis and Topalis (2008). As part of daylight harvesting strategies, Kontadakis et al. (2018) demonstrate adoption of interior and exterior light shelf, as a component of the building façade; Lee et al. (2018) illustrate light-redirecting performance of an awning system (with a built-in light-shelf) with its energy saving-capability; use of anidolic reflector (i.e. light pipe) in the ceiling plenum was studied by Kennedy and O'Rourke (2015), and; light redirecting system through reflective louvers, Okasolar in-pane louver series was developed by Okalux (Okasolar, 2018), to demonstrate its energy saving capabilities. These daylighting strategies illustrate a global shift towards more efficient energy resource management, with its end-use lower energy consumption and attendant reduced carbon footprint potentialities.

#### 3.1.3 Adoption of CFD-integrated design process for informed decision-making in architectural design

Computational Fluid Dynamics (CFD) is a fast and effective computer-based numerical analysis simulation tool that analyzes complex fluid flows which evaluates ventilation, energy performance, design, and stability in the field of architecture, among others. It is used to model and quantify airflow-related cases (including ventilation, infiltration and dispersion of the contaminants), and test the wind-built environment interactions through numerical analysis. It enables the analysis of various shapes and environmental conditions (Lee et al, 2021; Merin Abbas & Gürsel Dino, 2019). It constitutes an important tool to understand current airflow designs, to reveal present shortcomings for improved ventilation and energy performance in particular (Melendez, Reilly & Duran, 2021). Within the CFD domain, Heating, ventilation and air conditioning (HVAC) systems can be manipulated to determine the optimal configuration for ventilation efficiency and energy performance. A typical illustration is Figure 4 of the CFD study carried out by Moosavi et al. (2014) which predicted air temperature in the naturally ventilated building with windward openings reduced to 0.1 m. The study shows the effects of minimizing windward opening size on indoor temperature distribution using CFD simulation tool.

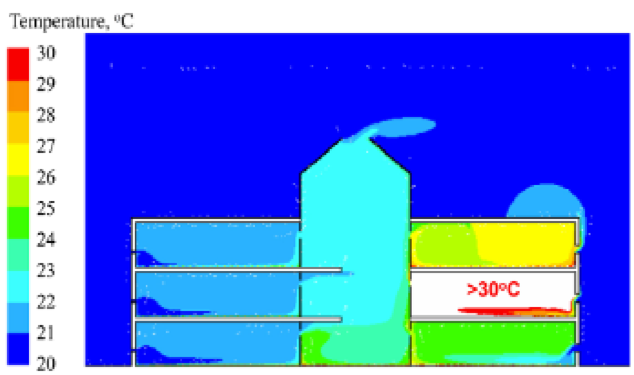



**Figure 4** Predicted air temperature in the naturally ventilated building with windward openings reduced to 0.1 m (Source: Moosavi et al, 2014)

In general, numerical analyses involving CFD are often carried out to evaluate building design and energy performances. Such information obtained by CFD assists in investigating the impact of building technologies, quantifying indoor environment quality, and integrating renewable energy systems (Moosavi et al., 2014). CFD modeling approach was used to determine the influence of building morphology on the efficiency of building-integrated wind turbines in Bahrain Trade Centre (Chaudhry, Calautit & Hughes (2015). The study highlighted the potentials of using advanced CFD to factor wind into the design of any architectural environment. Other studies inclusive of Jana, Sarkar & Bardhan (2020), Subhashini & Thirumaran (2020), Mora-Pérez, Guillén-Guillamón & López-Jiménez (2015), Lu and Sun (2014), Chong et al. (2014), Wu, Hung & Lin (2013), Mithraratne (2009), Chen (2004), have also demonstrated application of CFD-integrated design process for informed decision-making to evolve sustainable design solutions with reduced energy needs, to mitigate carbon emissions

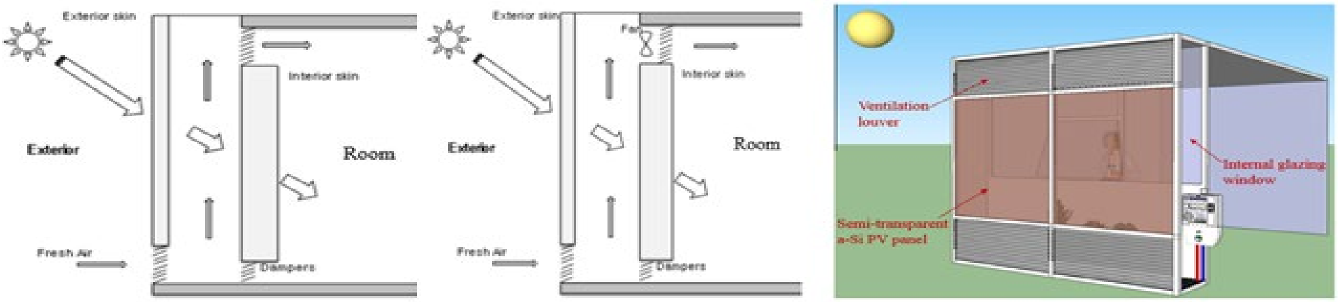
### *3.2 Post-Construction Technological Advancements*

This involves deployment of advanced technologies for building operations, through thermal harvesting, and management in secondary thermal applications, to optimize occupants' comfort and reduce building energy requirements (Cuce and Riffat, 2015). It involves exploration of new building techniques and development of technologies that harvest Infra-Red (i.e., thermal) solar energy which in turn, offsets the energy requirements of electrical systems for mechanical systems for heating/cooling needs. This concept may involve (but not limited to) any of the following approaches:

#### 3.2.1 Design of double skin facades (DSF)

This is a form of construction involving arrangement of separated two layers of façade curtain with an infill air cavity which can in turn be naturally or mechanically ventilated for controlled heat gains or for captured heated air which is used for space and water heating (Alva, Vlachokostas and Madamopoulos, 2020; Su, Li, and Xue, 2017). The need for this is borne out of the increasing costs of energy, necessity for reduction in energy consumption and growing concerns for environmental protection [European Commission, 2022). DSF integrated with photovoltaic modules reduces solar heat gain due to their high absorptivity and low transmittance. Previous work by Peng et al. (2016) shows that only one seventh of the incident solar energy passes through such DSF type as its direct solar heat gain coefficient is as low as 0.15. This is due to its ability to block much solar heat gains from passing through. As illustrated in Figure 5, the arrangement involves combinations of varying thermal masses (may be of Concrete, Sandcrete Block, Glass or Aluminium) (Fallahi et al., 2010).

Over the past decade, DSF has become an increasingly important feature in the architectural building design and operation, as its usage spreads across, to cover provision of: thermal buffer zones; solar preheating of ventilation air; energy saving; protection against wind, sound and pollutants, and; night cooling and space for energy collection devices like Photovoltaics cells. It has become an important feature of renewable thermal source to enhance clean energy utilization as quotient of carbon emissions is significantly reduced (Agathokleous and Kalogirou, 2016). In effect, it is an approach at building micro-level to combat climate change impacts on the environment. Studies carried out by Zhu et al. (2020), Luo et al. (2017), Su, Li and Xue (2017), Han, Lu, and Yang, (2010), Zhou and Chen (2010), De Gracia et al (2013), Gan (2009), Gratia and Herde (2004), Mei et al. (2003), Eicker et al (1999), among others, demonstrate material compositions, heat transfer methodologies, comparative energy performance and quantifications (relative to other renewable energy sources), dynamic thermal model and challenges associated with DSF integration in buildings. Essentially, when DSF is designed for optimal performance, it is capable of reducing energy needs in the building with the resulting positive impact on the global environment.




**(a)**[1] **(b)**[2] **(c)**[1]

**Figure 5** Schematic diagram of ventilation approach in a DSF: (a) naturally ventilated façade (b) mechanically ventilated façade; (c) mechanically ventilated façade (Sources: 1 – (Agathokleous and Kalogirou, 2016); 2 – (Peng et al., 2016)

### 3.2.2 Development of Building Integrated Photovoltaics (BIPV) façade

This is an advanced application of technologies in which building façade is substantially integrated with photovoltaics panels with a view to harvesting natural solar energy for building operation, with minimal impact on the environment. It is an emerging innovation in which building façade is converted into a clean renewable micro-energy-based generator as it satisfies the fundamental and conventional design objectives of aesthetics and environmental control (Attoye & Hassan, 2017; Peng, Lu and Yang, 2013), as illustrated in Figure 6.

(a) (b) (c) (d)

**Figure 6** Application of BIPV facades in architectural design: (a) White PV (b) Coloured PV panels (c) PV-powered media wall of Xicui Entertainment Complex in Beijing (d) Building integrated media energy display (Source: Sun et al, 2021)

If designed for optimal performance, the facades can facilitate significant reduction in heat gains and heat losses in summer and winter respectively, through the entire building envelope (Peng, Lu, & Yang, 2013). In particular, multiple gains such as reduced use of fossil fuels, lower carbon emissions, and decreasing emission of ozone depleting greenhouse gases, among others, are derived from BIPV façade technology (Zhang, Lu and Peng, 2017; Agathokleous and Kalogirou, 2016). Several studies affirm substantial energy saving capability of the technology with its reduced pollution and other environmental challenges associated with the conventional energy sources particularly, the negative impacts on the ecosystem (Elinwa, Radmehr, and Ogbeba, 2017; Bayoumi, 2017; Peng et al, 2016; Chow et al., 2010; Wong et al, 2008). It is a promising way of cutting down the environmental costs of fossil fuel energy generation as it is capable of delivering electrical energy at a lower cost compared with grid electricity, for certain end users (Song et al, 2016; Norton et al, 2011)

### 3.2.3 Integration of Evacuated Tube Solar Air Collector System

This is a form of solar energy harvesting technology in which heated air is transported through a horizontally placed absorber tubes integrated into glazing unit system, installed on a building facade (Alva, Vlachokostas and Madamopoulos, 2020; Maurer et al., 2012). Different configurations of evacuated tube solar collectors inclusive of U-type, H-type, T-type, heat pipe type, etc., exist (Ataee & Ameri, 2015; Nkwetta, & Smyth, 2012). Essentially, Evacuated U-tube solar collector consists of a heat exchanger which transfers the energy from Sun solar radiation to the working fluid. The system consists of an array of fixed-angled, tilted absorber slats connected to fluid piping and contained within three glass panes. Air is heated by convection through the sun-exposed tubing and returned into the building for potential use in mechanical systems (Maurer et al., 2017). Through radiative heat transfer process, the solar radiation incident on the outer glass surface of the evacuated tube is transferred to the inner glass tube. Then, the heat so generated is absorbed by the U-tube from where it is exchanged to the working fluid (Naik, Bhowmik, and Muthukumar, 2019). A typical illustration of this principle is shown in Figure 7 and Figure 8.

Several research works have been carried out to demonstrate potential energy saving capabilities of this technology by Singh and Vardhan (2021), Yildirim and Yurddas (2021), Naik, Bhowmik and Muthukumar (2019), Maurer et al. (2017), Gao et al. (2014), Maurer et al. (2012), among others. As an applicable technology, it is capable of generating building energy needs through clean and renewable energy source which combats climate change induced carbon emissions from fossil fuels.

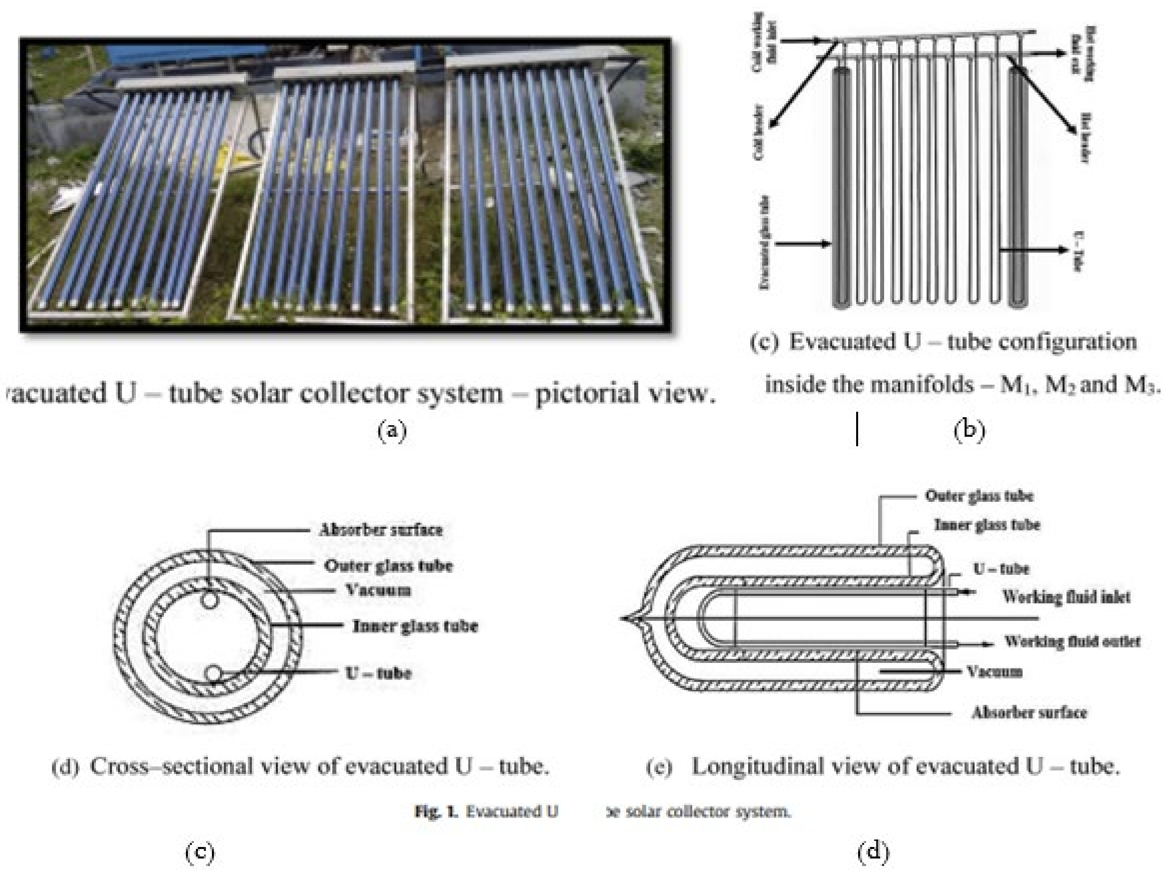



**Figure 7** Evacuated U-tube solar collector system: (a) Pictorial View (b) U-tube configuration inside the manifolds (c) Cross-sectional view of Evacuated U-tube (d) Longitudinal view of Evacuated U-tube (Source: Naik, Bhowmik & Muthukumar, 2019)

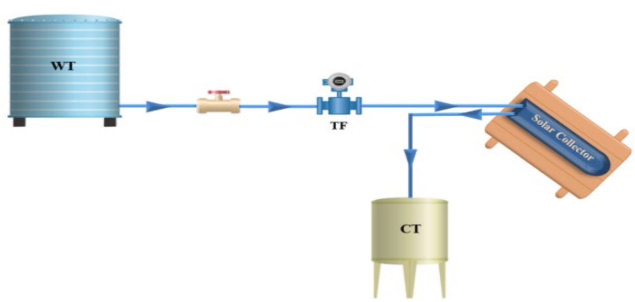



**Figure 8** Schematic View of solar collector system application in buildings (CT – Collection tank; TF – Turbine type flow metre; WT – Water tank) (Source: Kiran, Premnath & Muthukumar, 2021)

### 3.2.4 Adoption of Phase Change Material on Building façade

This represents a joint advanced technological deployment by related building professionals with a view to combating climate change impact at building micro-level. Phase Change Material (PCM) in this context refers to thermal energy storage (TES) material which absorbs heat (cold) from the environment and stores it, and releases same to the immediate environment at a later stage, when needed. This cycle of thermal energy exchange with their environment is completed in their process of phase change, to conserve energy usage, and reduce carbon emissions while regulating the comfort of the surrounding environment (Yichao et al., 2020; Wang et al., 2018). PCM, also known as latent heat storage material is characterized with high energy storage density and stable output temperature that constitute important features for improving its energy structure and utilization. With its high heat of fusion, it absorbs and releases heat at a nearly constant temperature, and has capacity to store 5–14 times more heat per unit volume than conventional sensible storage materials (Sharma, Chen & Buddhi, 2009). Its melting temperature is expected to be close to the human health and comfort temperature levels, according to the indoor thermal comfort conditions (approximately 25 °C). TES technology could be useful for domestic hot water or space heating and cooling purposes as PCM releases latent heat earlier absorbed during the phase change from solid to liquid. Its application in building as a component of building envelope facilitates smoothing of the diurnal temperature fluctuations, with the overall reduction in the building's energy consumption (Navarro et al., 2019; Zalba et al., 2003).

Right use of PCM can minimize the peak heating and cooling loads, thereby downsizing cooling/heating systems, and has the capability to keep the indoor temperature within the comfort range due to smaller temperature fluctuations. Its main advantage is its ability to enhance the thermal storage potential with a minimum change of the existing building design (Harlé et al, 2022; Souayfanea, Fardouna, and Biwole, 2016). It can improve the thermal inertia of buildings, and improve their energy usage, which contributes to reduction of greenhouse gas emissions and therefore global warming (Harlé et al, 2022). In residential buildings, between cooling and heating energy savings of 5 and 30% can be attained with the application of PCM on thermal mass in well insulated structures (Souayfane, Fardoun, and Biwole, 2016; Kosny, 2015). It can be integrated into the building envelope through direct incorporation, immersion, shape-stabilization, micro-encapsulation and macro-encapsulation (Liu et al, 2018; Wahid et al., 2017; Konuklu, Paksoy & Charvat, 2015). They can also be incorporated into finish materials, thermal insulation or structural components (Kosny, 2015). Schematic illustrations (sectional views) of PCM in new construction, retrofit, flooring and ceiling applications are shown in Figure 9 and Figure 10.

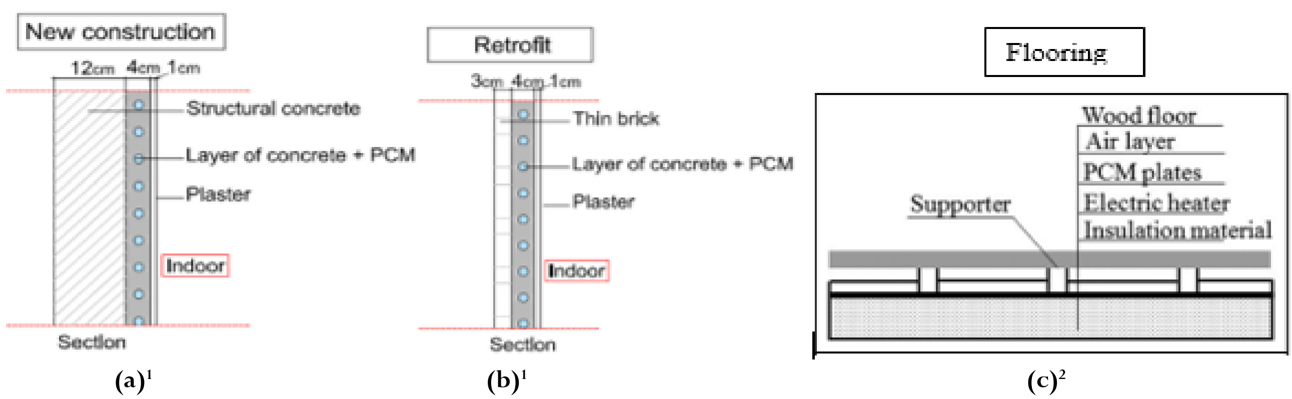



**Figure 9** Schematic Phase Change Material applications in: (a) new construction (b) retrofit, and; (c) flooring (sources: 1 – Navarro et al, 2019; 2 – Cui et al, 2017)

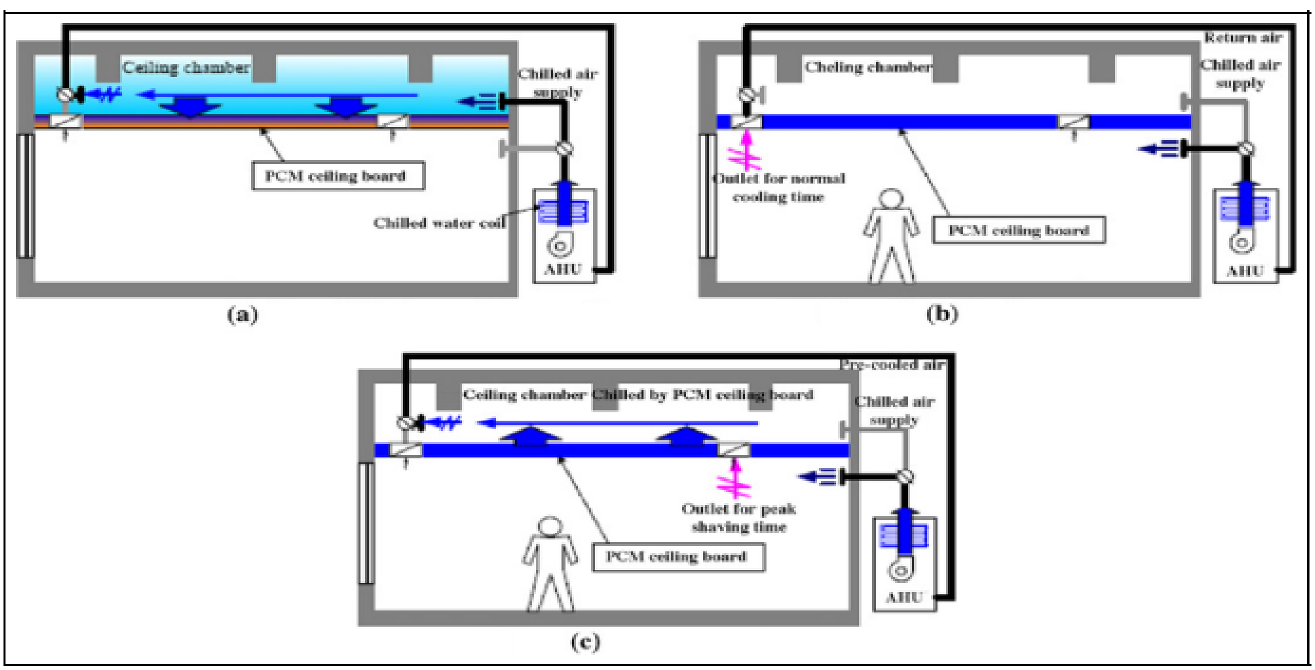



**Figure 10** Schematic Phase Change Material applications in ceiling: (a) overnight thermal storage time (b) normal cooling time, and; (c) peak shaving control time (source: Cui et al, 2017)

Apart from the common inorganic and organic PCM, also in existence are the monolithic and binary or multicomponent composite (eutectic mixtures) types (Li et al., 2017). For effective energy saving, building structure, climate, environment, and the purpose of using PCM, have significant role to play. In particular, varieties of PCM applications (such as paraffin, fatty acid, hydrated salt, eutectic), integrated in building envelope in varying climatic regions differ as Figure 11 presents a global survey of different PCMs in use, on a world map with identified varying climatic sub-areas. The figure describes PCMs usage/applications in different cities of the world, to emphasize its global acceptability.

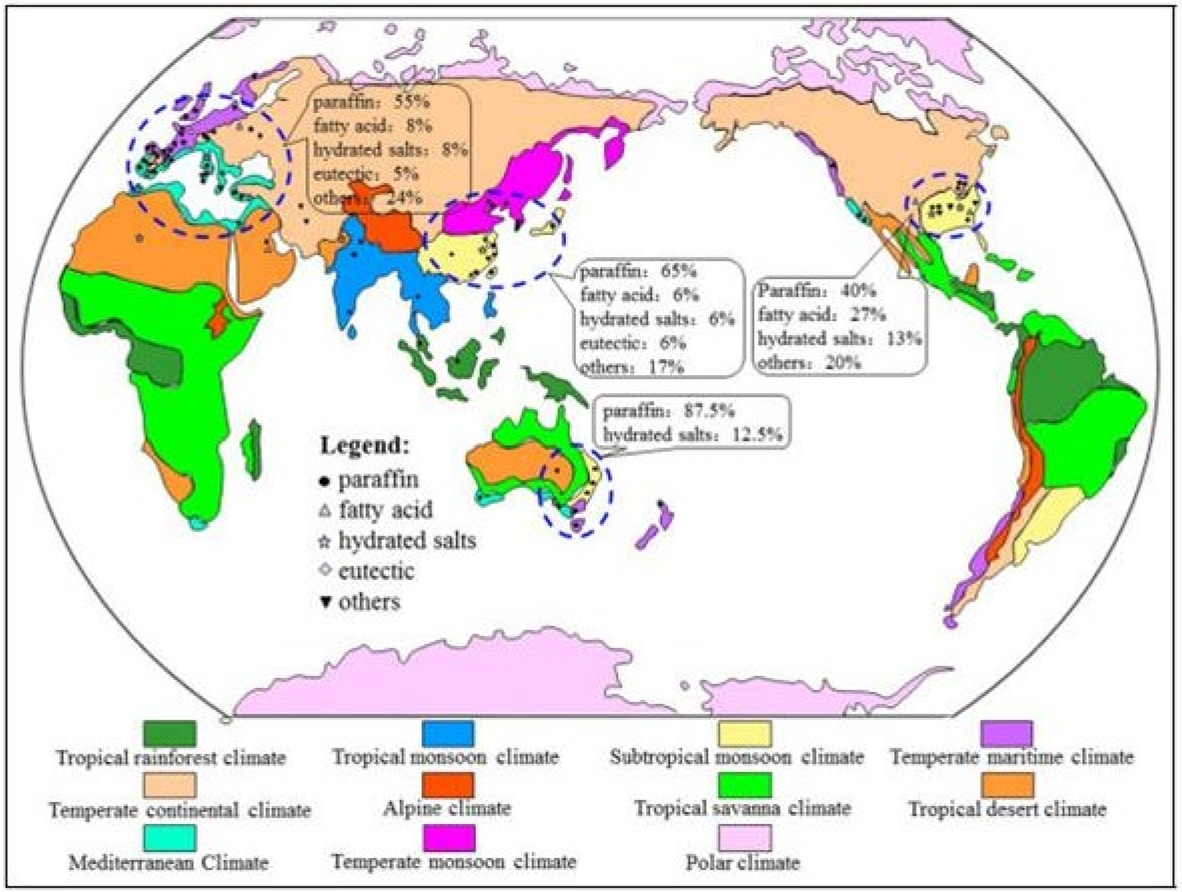



**Figure 11** Adoption of varying Phase Change Material applications in different Climatic Regions (source: Cui et al, 2017)

Previous studies inclusive of Shah et al. (2022), Liu et al (2018), Cui et al. (2017), Genc & Karagoz (2017), Kalnæs & Jelle (2015), Memon (2014), Zhou, Zhao and Tian (2012), among others, have been conducted to explore possibilities of integrating PCM into building design as new constructions and retrofits.

### 3.2.5 Implementation of Life Cycle Energy Analysis Policy on New Construction

Life cycle energy analysis (LCEA) is one of the several tools for analysing and minimizing environmental impacts of building construction as it minimizes the risk of shifting an environmental impact from one part of the life cycle to another (Paulsen & Sposto, 2013). It is an approach through which all energy inputs into a building throughout its life cycle, from 'cradle to grave' are accounted for (IPCC, 2007; Cabeza et al, 2014). Implementation of LCEA policy requires substantial professional and technical expertise especially, on new construction works, to account for the energy use at different phases of the construction cycle, with a view to reducing carbon emissions. These phases include those of manufacturing (i.e., embodied energy), building operation (i.e., operating energy), and final demolition (i.e., demolition energy) (Stephan, Crawford & de Myttenaere, 2013). As graphically illustrated in Figure 12, manufacturing phase includes manufacturing and transportation of building materials as well as technical installations used in building construction, with a typical comparison of Global Warming Potential by Life Cycle Energy Analysis at this Stage (Embodied Effects), as illustrated in Figure 13.

## 4. Conclusion

Increasing urbanization resulting from the growing population necessitates the need for more infrastructural facilities particularly, housing, among others, with its attendant energy utilization, and consequent negative impacts on the environment. Thus, there is the need for innovative ways to optimize energy use in buildings, to lessen the impact of climate change, due to increasing carbon emissions from building construction and operation. This is emphasized with the promulgation of the seventeen-point United Nation's Sustainable Development Goal 2030 (SDG-2030) Agenda with particular reference to Agenda Thirteen (Agenda-13) which encompasses the need for urgent action to combat Climate Change. Within this context, this submission has discussed beneficial impact of emerging technologies through collaborative efforts of the relevant professionals within the built environment, to address the pandemic climate change related challenges. In particular, the submission focuses on the application of the emerging technologies at both pre and post construction stages for more optimized energy utilization and reduced carbon footprint particularly, at the building micro level. This is a collaborative effort towards realization of the SDG-2030 Agenda Thirteen (Agenda-13) in particular, for overall sustainable clean and safe global environment..

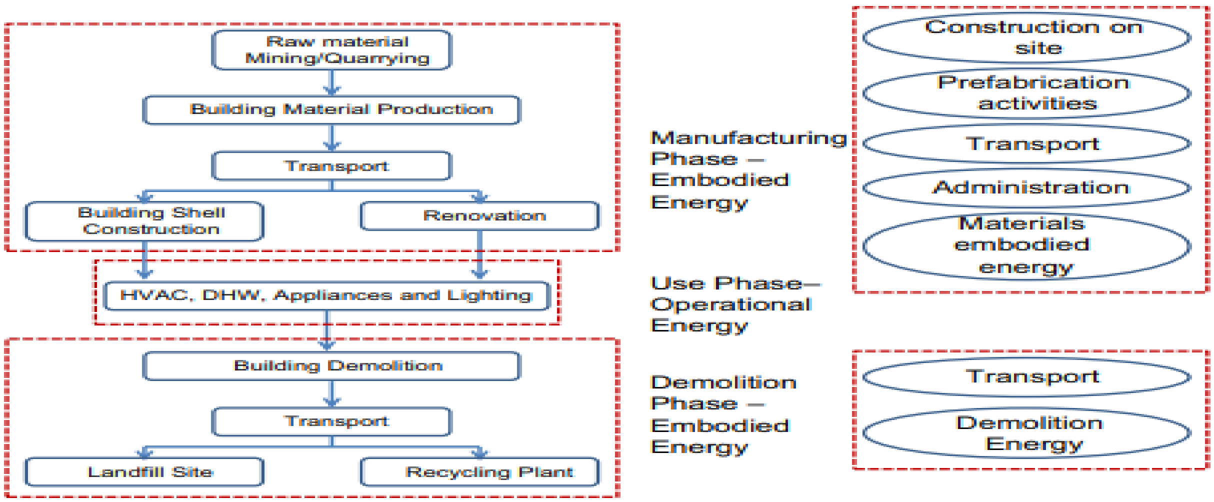



**Figure 12** Life Cycle Energy Analysis of a building (source: Cabeza et al., 2013)

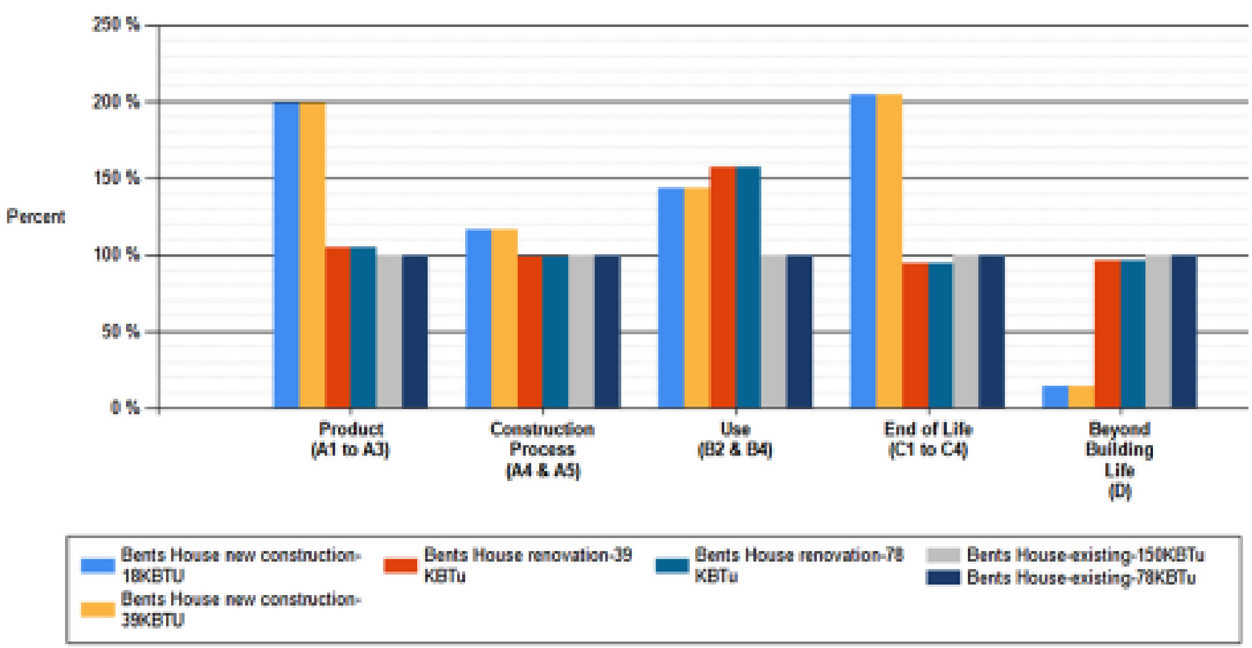



**Figure 13** Comparison of Global Warming Potential by Life Cycle Stage (Embodied Effects) (source: Hu, 2017)

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