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Design review on indoor environment of museum buildings in hot-humid tropical climate

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Abstract. Museum buildings display artefacts for public education and enjoyment, ensuring their long-term safety and the comfort of visitors by following strict indoor environment control protocols using mechanical Heating, Ventilation and Air Conditioning (HVAC) systems to keep the (environmental) variables at a fixed comfort level. Maintaining this requires constant supply of energy currently mostly sourced from the combustion of fossil fuels which exacerbates climate change. However, a review on the effects of the indoor environmental variables on museum artefacts as well as museum visitors revealed that there is no specific point at which artefact deterioration occurs, and that there are wide ranges of conditions that guarantee the long-term safety of artefacts and human comfort. Visits to museum buildings in hot-humid tropical climate of Nigeria revealed that strict indoor environmental practices were adopted. Even when appropriate micro-climatic conditions are provided for artefacts, mechanical HVAC systems remain necessary for visitor comfort because almost no consideration is given to natural ventilation. With the current global push towards energy management, this paper reviewed passive environmental control practices, architectural design strategies, and discusses the adaptation of double skin façade with jali screens, and the notion of smart materials, which can satisfy the range of requirements for the long-term safety of artefacts and levels of human comfort in buildings in hot-humid tropical climate, without mechanical HVAC systems. This review would inspire more discussions on passive, energy efficient, smart and climate responsible popular architecture, challenging current thinking on the impact of the more accepted representative architecture.

Keywords: double skin façade; energy efficiency; indoor environment; mechanical HVAC; museum buildings; passive design; smart materials

1. Introduction

Museums are established to promote an understanding of the natural world, the history of past and present civilizations, as well as humanity's artistic, scientific, and technological achievements (Ellen 2008, Feng 2016). According to Miller and Miller (1994), they collect significant scientific, aesthetic or historic objects of interest, also known as artefacts, care for them, study, and display

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them for the purposes of educating the public as well as the general advancement of knowledge. From classical antiquity, natural and man-made art objects were heaped together on walls and ceilings, in what became known as a cabinet of curiosities to surprise as well as delight guests (Patricia 2002, Carlins 2015). These objects were exposed to the same ambient environmental conditions as guests (Erhardt *et al*. 2007), and it was later discovered that this accelerated their deterioration. In the 19th century, a concern to not only gather, but also preserve objects from the past started, and what followed for approximately the next century, was the founding, by several authorities throughout the world, of buildings expressly intended for the safe display of artefacts and the good of the general public (Geoffrey, 2020). In China, the number of publicly accessible museum buildings has increased significantly. Based on the country's national long-term outline plan for museum development (2011-2020), Feng (2016) projects that there will be one museum for every quarter million people. Indeed, with the increasing number of museums around the world and concern for the long-term safety of the objects they display, the environmental conditions around them have been revealed to be of utmost importance (Kramer *et al*. 2016) in order to ensure that humanity's cultural heritage can be passed on to future generations, as acknowledged by Agnes (2006).

Generally, objects interact with their immediate surroundings, always seeking to attain a balance with the environment. Museum artefacts naturally seek to attain this state of physical and chemical equilibrium with their environment, leading to deterioration. The National Park Service (NPS 1999) identified four variables that can accelerate this process in addition to causing discomfort to museum visitors. Also called environmental agents of deterioration, they include temperature, relative humidity, light, and air pollution. While high temperature causes gradual breakdown or disintegration and discoloration of organic materials, low temperature causes embrittlement resulting in fractures of paints. These temperature changes and fluctuations also result in changes in the humidity of the air and thus, its moisture carrying capacity. Museum artefacts are vulnerable to damage caused by these changes. The indoor environment of museum buildings also significantly affects human performance; unfavorable air temperatures can have considerable effects on biological or physiological responses and cognitive functions (Abbasi *et al*. 2019). Additionally, according to Askari and Altan (2014), the environmental conditions that favor museum artefacts may not meet the requirements of museum visitors at all times. Consequently, a fixed 'flat line' value for temperature, and thus humidity, for both artefacts and visitors, has been recommended in museum buildings (Pietro *et al*. 2020, Taylor and Heinzerling 2018), leading to the adoption of controlled or mechanical Heating, Ventilation, and Air Conditioning (HVAC) systems as ideal indoor environment regulation/climate control tools described by Franciza (2006), regardless of outdoor conditions. These systems become essential, and according to the Smithsonian Institution (2012), require 24hour operation, and thus, a constant supply of energy currently mostly sourced from the combustion of fossil fuels, exacerbating climate change. With conditioned air, fewer/no windows that allow natural/passive ventilation are required, because the humidity of the indoor air can be actively regulated (Vaughn 2008). However, there are several problems associated with the use of HVAC systems (Matheos 2006); they are expensive to install, operate and maintain. Furthermore, the building industry is already responsible for almost 50% of the world's energy consumption, with 27% of this being consumed by air conditioning and lighting alone (Matthias and Alex 2006). There is also the associated humidifying which favors mould growth because these air conditioning systems are, in practice, not kept on throughout the day (Edgar and Henk 2008). Also, refrigerant gases used in these air conditioning installations contribute to global warming, and dirty filters from poorly maintained systems may actually bring contaminated air into buildings (Matheos 2006).

Current study presents a shift from the use of mechanical air conditioning (HVAC) systems, and explores other approaches/control systems that are economical, sustainable and just as efficient in regulating the indoor environment (Edgar and Henk 2008, Shin and Franciza 2001, Patricia 2002, Ikechukwu and Moses 2019). This shift is also beginning to inspire the thinking that answers to indoor environmental problems hinge on developments and advances in building physics and materials science via the notion of environmentally adaptive smart materials. Typically defined as exceptionally or unusually structured substances which manifest quick response to their surroundings, smart materials can be designed to have one or more properties which can be significantly altered or changed in response to external (environmental) stimuli (Lianbin and Peng 2016, Ogwu and Nzewi 2017). Other notions like the adaptation of the double skin façade and climate responsible popular architecture are also explored and discussed.

Additionally, because most museum buildings are purpose built, the consideration of constructability issues at the design stage can lead to improved performance. Abdelaziz *et al.* (2018) discussed the value obtained by integrating construction knowledge with the building design process, and its benefits for designers and occupants alike. Indeed, there is need for a decision support tool to aid designers in reviewing their design. Such tools are beneficial at the conceptual design stage when there is a room to improve the design significantly, and ICT is argued to provide solutions for associated challenges towards integrated design, providing ease of assessing multiple design objectives including cost, sustainability, safety, security, constructability, accessibility, (Abdelaziz and Walid 2017) as well as the buildings post-construction ecological footprint. Already, models of risk management for construction projects have been developed using rigorous and precise mathematical models. This practice according to Amina and Mohamed (2020), is necessary in minimizing the level of risk and treatment of identified hazards. A full comparative study of multi-objective meta-heuristics (MOMHs) for optimum design described by Apichit *et al.* (2017), or high-performance architecture, which uses optimization to find the building form, orientation, window size, etc (Bomin and Youngjin 2017), can also contribute to mitigate the impact of mechanical HVAC in buildings.

2. Methodology

The museum indoor environment is considered important. The effects of the four identified indoor environment agents of deterioration (temperature, relative humidity, light and air pollution), on museum artefacts and museum visitors were reviewed in the current study. Visits were made to two purpose-built museum buildings in Nigeria to observe their indoor environment control strategies. An extensive search was also conducted to identify literature on museum indoor environment. Queries were run using open, publicly accessible search platforms, with the keywords "museum" and "indoor environment". Emphasis was placed on published journal articles and books that referenced environmental control practices adopted by museum institutions, and those that had the words 'museum' and 'environment' in their title. Specific publications from museum institutions were also considered. Query results were limited to publications in the English language. It was observed that the query results connected 'museum indoor environment' to 'mechanical HVAC' and the current global call for 'energy efficiency'. It is in line with this that current study explored alternative notions for the control of the indoor environment without mechanical HVAC systems. This however, also revealed the need for region specific solutions, hence the inclusion of 'hot-humid tropical climate' to the title.

Table 1 Allowable temperature, relative humidity and light ranges for museum buildings (Antoniewicz and Mroz 1999)

Space	Temperature (°C)	Relative Humidity/RH (%)	Light (lx)
storage	16 - 18	50 - 65	50 - 150
exhibition	18 - 24	50 - 65	50 - 150

Table 2 Recommended temperature and relative humidity in various climatic zone (Consortium for Heritage Collections and their Environment 2002)

Climate	Temperature (°C)	RH (%)	Remarks
humid tropics	22 - 28	55 - 70	Acceptable for mixed collections. However, RH too high for bronzes containing iron and chloride. Air circulation very important.
temperate coastal and other non-arid regions	18 - 24	45 - 65	Recommended for galleries with paintings, furniture, and wooden sculpture in Europe, satisfactory for mixed collections. May cause condensation and frosting difficulties in old buildings, especially inland Europe and northern North America.
temperate inland regions	18 - 24	45 - 65	A compromise for mixed collections and where condensation may be a problem. May be best for textiles and paper exposed to light
arid regions	22 - 28	40 - 60	Acceptable for display of metal-only collections.

3. The museum indoor environment

According to Gary (1973), the first and major duty of museum organizations is to make artefacts accessible to the public, while at the same time, ensuring their safety. To achieve this, the rate of artefact deterioration must be slowed down, while at the same time, ensuring the comfort of visitors. A review on the indoor environment provides an understanding of its relationship with artefact deterioration, which was first seen in efforts to move and conserve the artefacts from Europe's great national museum during both world wars. It was observed that the resultant environmental conditions from temporary storage in mines, scaled down conservation time (Foekje *et al*. 2014). Now while there remains a great deal of uncertainty about the specific point at which damage of museum artefacts actually occur, and the general notion of good or bad climate (Paul 2014), temperature and relative humidity have been revealed to have the highest impact (Tomasz and Tomasz 2001) with emphasis placed on avoiding extremes (especially extreme fluctuations), rather than precisely hitting a specific range. Nonetheless, Antoniewicz and Mroz (1999) reveal allowable ranges of temperature, relative humidity, and light for spaces in museum buildings shown Table 1, and the Consortium for Heritage Collections and their Environment (2002) list the recommended conditions for different climatic regions with corresponding artefact types, shown in Table 2. Institutions have also issued standards and specifications for temperature and relative humidity, since the 1970s in the UK (Jane and Shumeng 2013, Lukasz 2013), to ensure the long-term safety of artefacts (see Table 3). These standards, however, continue to change as knowledge on the effects of climate on artefacts continue to grow, and a push made towards sustainability and energy efficiency of museum buildings.

Table 3 Institutions standards for temperature and relative humidity (Jane and Shumeng 2013, Lukasz 2013)

Year	Institution	Temperature (°C)	Relative Humidity (%)			Remarks
			Long term average	Seasonal cycle	Short term fluctuations	
1978	Gary Thomson The Museum Environment	19 (winter) - 24 (summer)	50 or 55	-	+/- 5	Acceptable for major existing national museums, and also for all important new museum buildings.
		Reasonably constant to stabilize RH	40 - 70			Aimed towards avoiding major dangers while keeping cost and alteration to a minimum, such as, climate control in historic houses and churches.
1979	Canadian Conservation Institute	21 (seasonal variation from 20 to 25 allowed)	47 - 53	38 - 55	+/- 2	The allowed seasonal changeover of the set points is 1ºC and 5% RH/month. Occasional variations of +/- 5% RH are tolerable if these are the exception.
1994	National Trust	5 - 22	58	50 - 65 (level 1) 40 - 75 (level 2)		The recommended strategy involved control of RH to as constant a level as possible principally by adjusting the heat input.
1999	American Society of Heating, Refrigerating and Air-Conditioning (ASHRAE)	15 -25	50 (or historic yearly average)	No	+/- 5	No risk of mechanical damage to most artefacts and paintings.
				No	+/- 10	Small risk of mechanical damage to high vulnerability artefacts; no mechanical risk to most artefacts, paintings.
				+10 in summer, -10 in winter	+/- 5	
				+10 in summer, -10 in winter	+/- 10	Moderate risk of mechanical damage to high vulnerability artefacts; tiny risk to most paintings.
				25 - 75		High risk of mechanical damage to high vulnerability artefacts; moderate risk to most paintings.
				Below 75		High risk of sudden or cumulative mechanical damage to most artefacts and paintings because of low humidity fracture.
2006	National Trust	5 - 22	50 - 65	-	-	The earlier fixed set point of 58% RH was replaced with a target range. The RH set point should be adjustable in each room and depend on the conditions to which the collection has acclimatized.
2007	Smithsonian	21	45	-	+/- 8	

	Institution					
2009	National Museum Director's conference, UK	16 - 25		40 - 60		Specifications for the majority of objects containing hygroscopic material. However, panel paintings are listed among more sensitive materials which require specific and tight RH control.
2010	European standard EN 15757:2010	No specification	Historic yearly average	Historic seasonal cycle	+/- 10 or target range calculated from the historic climate (whichever is greater)	This cycle is obtained by calculating, for each RH reading, the central moving average (MA), which is the mean of RH readings taken 15days before and after the time at which the average is computed. The lower and upper limits of the target range of RH fluctuations are determined as the 7th and 93rd percentiles of the fluctuations recorded in the monitoring period respectively. A fluctuation is calculated relative to MA, i.e., the seasonal cycle rather than the yearly average value.

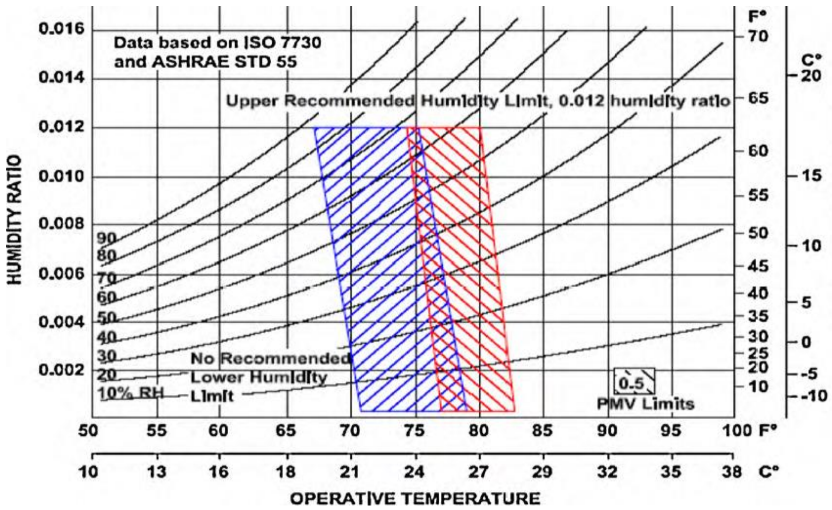


Fig. 1 Comfort Zone (ASHRAE STD 55-2004) (Thammanoon *et al*. 2010)

For museum visitors, the indoor environment has a great influence on one's sense of comfort and wellbeing. Comfort is generally described as the absence of discomfort, and according to Vaughn (2008), it is a set of conditions that do not cause any unpleasant sensations of temperature, humidity, or other aspects of the environment. Although humans can adapt to variations in the environment, a range of climatic conditions called the comfort zone, have been identified within which the majority of people would not feel discomfort of either heat or cold (Ali and Marafia 1988). Standards have also specified conditions in which some people will find the indoor environment comfortable (see Fig. 1).

The identified indoor environment variables are discussed further.

3.1 Temperature

Temperature is one of the key attributes of an object that determines if it is in thermal equilibrium with another object (Landis 2008). It is a measure of the movement or vibration of molecules in a material (NPS 1999). Thus, when it increases, the molecules move faster and spread out, then the material expands. When it decreases, the molecules slow down and come closer together, then the material contracts. Fluctuating temperature cause materials to expand and contract rapidly, setting up destructive stresses in objects. Additionally, high temperatures lead to increased chemical reactions. It can cause the breakdown of cellulose nitrate film which can lead to a fire if undetected. High temperatures also favor some biological activity, causing insects to breed faster. Wax collects dust more easily at high temperature, adhesives fail, and magnetic tape may become also become gooey at high temperatures. Temperature also has an inverse relationship with humidity, which in turn affects health and comfort of humans. Temperature ranges have been suggested for different areas in the museum building. In exhibition, storage and research areas, the safe temperature range is stated to be between 18-24°C; this is also within recommended thermal comfort zone of 21-23°C for humans (Dianne 2018).

3.2 Relative Humidity (RH)

Relative Humidity refers to the relationship between the volume of air and the amount of water vapor it holds at a particular temperature (NPS 1999). It is considered an important indoor environment variable because of the role water plays in various (chemical and physical) forms of deterioration. Materials can absorb and emit water depending on the relative humidity of the surrounding air. The temperature of the air determines how much moisture it can hold. When the temperature goes up, the RH goes down and when temperature goes down, the RH goes up. In most museum buildings, it is common practice to actively control/regulate the temperature using mechanical systems. In the evenings, when activity is reduced and people are not present, the temperature is turned down. However, turning it up again the following morning creates swings in RH. The RH affects museum artefacts in a number of ways: low RH levels cause shrinkage, warping, and cracking of wood and ivory; shrinkage, stiffening, cracking, and flaking of photographic emulsions and leather, as well as drying up of paper and adhesives. High RH levels cause swelling and can make adhesives or sizing softer or sticky; paper may cockle or buckle; stretched canvas paintings may become too slack. High humidity also aids biological activity. Mould growth is also more likely as RH rises, excessive exposure to which cause of a variety of health effects in humans ranging from minor allergic reactions and exacerbation of asthma to brain damage (Davis 2001). These effects can however be minimized by maintaining indoor RH levels between 40 and 60% (Thammanoon *et al*. 2010).

3.3 Light

Light is generally described as a form of energy visible to the human eye that is emitted or given off by moving charged particles (Marburger 2008). Light stimulates the sense of vision in

Table 4 Standards of illuminance for museum artefacts (Conservation Center for Art and Historic Artefacts 2020)

Illuminance (lx)	Sensitivity	Artefact type
50	Light-sensitive	Dyed organic materials, textiles, watercolors, photographs, blueprints, tapestries, prints and drawings, manuscripts, leather, wallpapers, biological specimens, fur and feathers.
150	Less light-sensitive	Un-dyed organic materials, oil and tempera paintings, finished wooden surfaces.
300	Not light-sensitive	Metals, stone, ceramics, some glass.

Table 5 Recommended illuminance for some human activities (Ibrahim 2007, Zumtobel Lighting GmbH 2018, Peter and Peter 2009)

Space	Activity	Illuminance (lx)
Office, Kitchen	Writing, reading, data processing.	500
Office	Front desk, meeting rooms, archives/document stores, board rooms.	300
Retail premises	Sales area.	300
Classroom, library	Educational, seminar, music, art	300
Office	Storerooms (bulk items), security rooms, entrance halls.	200
Entrance hall	Public assembly	100
Corridor	Public assembly	100
Ward (general lighting)	Health care	100
Public spaces	Short-term visits	50

humans serving to reveal artefacts with effect, maintain security, provide assistance for exit (Peter and Peter 2009) as well as general conditions for sight, especially at night. Light is also an agent of deterioration resulting in fading, darkening, yellowing, and a host of other chemical and physical changes in museum artefacts. It has both electrical and magnetic properties, so it is known as electromagnetic radiation, and is part of the electromagnetic spectrum, which is the complete continuum of all forms of light including radio waves, cell phone waves, microwaves, radar waves, infrared (IR) light waves, visible light waves, Ultra Violet (UV) light waves, x-ray waves, and gamma waves (Ibrahim 2007). All light types in museums, from daylight to fluorescent lamps, incandescent (tungsten), and tungsten-halogen lamps, emit varying degrees of Ultra Violet (UV) radiation - the most damaging to museum artefacts, and infrared (IR) radiation, which causes damage by photochemical action making surface layers of artefacts expand by radiant heating (Peter and Peter 2009).

For humans, the visible waves of the spectrum is perceived as light that is needed to see, the strength of which called illuminance, is measured in lux (lx) (NPS 1999). Defined as the quantity of luminous flux (quantity of light emitted by a light source) falling on a surface/plane (Ibrahim 2007, Zumtobel Lighting GmbH 2018), standards of illuminance have been recommended for several categories of museum artefacts (see Table 4), and for some human indoor activities (see Table 5).This implies that with harmful UV and IR radiation eliminated, spaces where non-light sensitive materials are displayed are also, in part, conducive for seminars and lectures, and other areas with light sensitive materials can also be conducive for short term visits.

Table 6 Common pollutants in museums and their effects on artefacts (Elyse and Sara 2019)

Pollutant	Common sources	Effects on artefacts
Sulphur dioxide (SO_2)	Fossil fuel combustion, pulp and paper production, biological activity, fuels for cooking and heating, vulcanized rubber	Metal corrosion, dye fading, paper and textile embrittlement, photograph deterioration, pigment darkening, calcium carbonate deterioration
Ozone (O_3)	Smog, photocopiers, laser printers, electrostatic particle filters	Rubber embrittlement, dye and pigment fading, photograph and book deterioration, textile and cellulose embrittlement, ink-jet print fading
Nitrogen dioxide (NO_2)	Biological processes, fossil fuel combustion, cellulose nitrate decomposition, tobacco smoke, photocopiers	Textile dye fading, textile embrittlement, photographic film deterioration
Hydrogen sulfide (H_2S)	Fuel combustion, wool, silk, felt, vulcanized rubber, waterlogged archeological organic materials, biological processes, pyrite collections	Silver and copper corrosion, lead pigment darkening, stone deterioration
Acetic acid (CH_3COOH)	Wood products, biological processes, laminated materials, paints, adhesives, sealants, cellulose acetate deterioration	Metal corrosion (lead, zinc, bronze), deterioration of calcareous materials (shell, fossils, limestone), cellulose embrittlement and glass deterioration
Formic acid (CH_2O_2)	Formaldehyde oxidation, drying oil paint, wood products, adhesives, sealants	Metal corrosion (lead, zinc, bronze), deterioration of calcareous materials (shell, fossils, limestone), cellulose embrittlement
Formaldehyde (CH_2O)	Wood products, resins, natural history specimens, fiberglass, photocopiers, textiles, PVC carpeting, laminates	Protein embrittlement (leather, parchment, animal hides), dye fading, pigment deterioration, textile deterioration
Acetaldehyde (CH_3CHO)	Textile industry, wood composites	Oxidizes to acetic acid in the presence of strong oxidants

3.4 Air pollution

Pollution generally refers to the contamination of the physical environment with pollutants (contaminants) that disrupt human health, the quality of life, or the normal functioning of living organisms (Engelking 2008). According to Grzyacz (2006), these pollutants are usually present in the environment but cause harm when in amounts more than normal, especially due to the activities of human beings. Air pollution or contamination of the air in museum buildings results from pollutants within as well as outside the (museum) building. They are categorized into two; particulate pollutants (includes dirt, dust, soot, ash, moulds and fibers), and gaseous pollutants (includes sulphur dioxide, hydrogen sulphide, nitrogen dioxide, formaldehyde, ozone, formic and acetic acids). They can be brought indoors through the HVAC system, (unprotected open) windows, or some building materials such as wood (which can release acids), glues used to attach carpets (that can release formaldehyde), and plastics (that release plasticizers and harmful degradation products such as phthalates and acids). Although the effects of pollutants are limited in the short-term, the long-term effects are severe resulting in color change or surface deterioration of museum artefacts (Thodoros *et al*. 2018) and other effects as shown in Table 6 below. Air pollution also creates a sense of discomfort in museum visitors manifesting in odors and sick-building or sick-house syndrome - a medical condition in humans directly linked to spending (too much) time indoors, due also in part, to the use of mechanical HVAC, and the slow exchange of contaminated indoor air with clean outdoor air (Yukio *et al*. 2017).

4. Discussion

The effects of four indoor environment agents of deterioration on museum artefacts and museum visitors were reviewed in the current study. While it is agreed that no specific environmental condition will satisfy all museum artefacts (Marion *et al*. 2004) as well as guarantee visitor comfort at the same time, current study highlights and discusses passive environmental control practices, architectural design strategies, adaptation of the double skin façade with jali screens, as well as the notion of environmentally responsive smart materials, which can satisfy the range of requirements for the long term safety of museum artefacts and satisfactory levels of human comfort in buildings in hot-humid tropical climate, without mechanical HVAC control systems.

4.1 Environment control practices

Several strategies to passively control the indoor environment agents of deterioration have been identified and classified into preventive conservation measures and architectural design strategies.

4.1.1 Preventive conservation

Preventive conservation measures involve the formulation and implementation of policies on artefact management, and best indoor environment control practices that can be adopted by museum administrators and conservationists. According to Stefan (2004), these practices include avoiding intense light/direct sunlight/powerful electric light on colored artefacts, as well as eliminating harmful UV radiation by installing filters for windows or glass on framed artefacts. Other practices include avoiding turning HVAC equipment on during the day and off at night (this can cause daily fluctuations in RH); actively limiting the number of people in a room (RH can increase from moisture introduced by breathing and perspiration); artefact zoning by placing light sensitive artefacts away from spotlights, external walls, air vents, entrance doorways etc; and maintaining artefacts that need tighter control within controlled microclimates (Marion *et al*. 2004) in cases, boxes, and folders. Artefacts should also be monitored regularly to quickly identify any damages; wall and display surfaces should be regularly cleaned to minimize the accumulation of dust; seals and weather stripping around doors should be constantly checked and properly maintained (to keep pollutants out); sensitive objects should be stored in appropriate museum specimen cabinets with sound gaskets; and air filters can be used to remove particulates from the air (NPS 1999).

4.1.2 Architectural design strategies

According to Salvadori (1980), buildings are created with intent, to serve a purpose. As solutions to one of the basic needs of man, they function to protect from the elements, as well as establish space for various activities. The nature of the purpose notwithstanding, architecture, and the process thereof (otherwise known as design), results in a product that is a solution to an identified need. Architecture thus, has been described as a ‘problem-solving design process’ (Francis 2015).

With museum buildings, the 'problem' is identified as that of ensuring the long-term safety of artefacts and human comfort. Already, the revealed indoor environment requirements for buildings, occupants and the majority of artefacts, fall within relatively wide, safe and acceptable ranges (Marion *et al*. 2004). These can be maintained by alternative (indoor environment control) measures without mechanical intervention, via the adoption of passive (architectural) design (strategies). Defined as (design) strategies that use natural energy flows, appropriate building orientation, building materials, shading, the building envelops and passive technologies to keep indoor environmental conditions within comfortable limits, passive design eliminates the dependence on mechanical HVAC systems (Hasim *et al*. 2016), while ensuring consistent fresh air in buildings, reducing mould growth from relative humidity build-up, low-zero heating/cooling costs and a generally improved indoor environment (Passivhaus Trust 2020). These strategies also conform in part, to the notion of sustainable architecture, which among other things, is architecture that is suitable to particular climates, materials and cultures (Joo-Hwa and Boon Lay 2006). Current study examines the adaptation of these strategies in the tropics.

The tropics, identified as the area between the regions of Cancer and Capricorn, has two major classifications - the hot-humid and the arid/semi-arid tropical climates, with average temperature of above 18°C (Blair 2014). Daily outdoor and annual temperature variations in the hot-humid tropical region is small, but solar radiation is intense and humidity is high. Consequently, architectural design strategies that offer best protection against direct/diffuse radiation and enhance natural ventilation to dissipate heat and reduce indoor humidity are recommended.

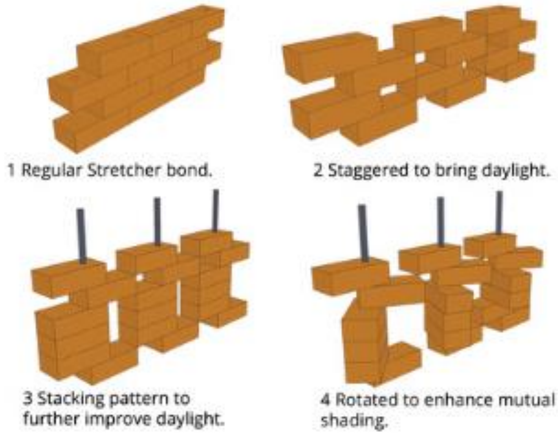
4.1.2.1 Double Skin Façade (DSF) adaptation

The impact of solar radiation is very intense in the tropics. Consequently, it is recommended that perimeter walls of buildings be shaded from the sun at all times (Cairns Regional Council 2011). The primary application of the façade concept is to minimize this impact of solar radiation in buildings (Gerhard *et al*. 2011) serving to trap or dissipate heat. Defined as an additional external cover over the existing traditional façade (also called skins) that can optimize the indoor environmental conditions and reduce the demand for active cooling, double skin façade (DSF) provides an effective means of regulating heat, light, air, and noise in buildings (European Commission Directorate 2001). Originally inspired by the aesthetic desire for an all-glass façade (Harris 2004), DSF affects other interacting building variables, including daylight, natural ventilation, indoor air quality, acoustics, thermal and visual comfort, energy use, environmental profile, etc. DSF essentially involves a pair of skins and the space between them which acts as insulation against temperature extremes, winds, and sound (Saelens and Hens 2001, Claessens and DeHerde 2010).

The space between the skins can be naturally or mechanically ventilated and may vary in width from 200mm to more than 2000mm (BBRI 2002). For the naturally ventilated type, the extra skin provides additional thermal insulation during the periods with no solar radiation. In periods with solar radiation, the skin is naturally ventilated from the outside by stack effects - i.e., the air in the cavity rises when heated by the sun; solar heat gains are reduced as the warm air is expelled to the outside (Kragh 2000). DSF improves the comfort of building occupants, provide natural ventilation via windows that are both burglary proof and protected against the weather.

Although the notion of DSF was designed to be implemented in the temperate regions with glass skins, the same operational principles can gain full expression in regulating the indoor environment in hot-humid tropical regions using bricks as the outer external skin, forming an open beautiful screen which lets in subdued light, outdoor air via natural ventilation and can keep the

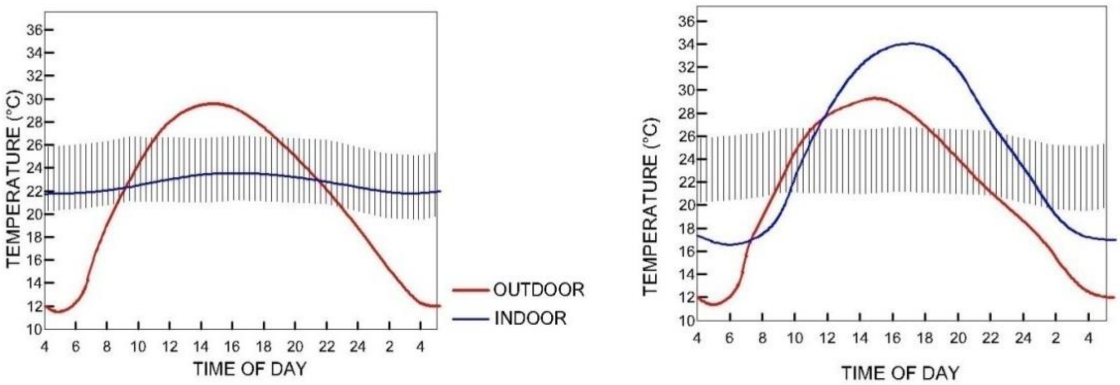
Fig. 2 Brick jali wall (Patti 2018)



(a) Rotated patterns of outer skin for enhanced shading and improved daylight

(b) Reduced indoor heat gain and illuminance levels

Fig. 3 Application of brick jali DSF in Boys Hostel project in Gurugram, India (Zero Energy Design Lab 2018)



(a) Temperature fluctuations in mud brick walls (b) Temperature fluctuations in concrete panel walls

Fig. 4 Indoor and Outdoor air temperature fluctuations within 24hours (Fathy 1986)

indoor temperature 5°C below the outdoor value (Patti 2018). Indeed, fired bricks can be made into versatile outer skins known in Indo-Islamic architecture as jail screen, while the second (main/traditional) skin can have varying degrees of controllable openings. Defined as a form of façade system made using perforated bricks or latticed screen, jali skins can act as mediators between the indoor and outdoor, providing selective shading, and constant flow of breeze ensuring occupant comfort in hot-humid tropical climates (Nalin 2014). The notion of the brick jali walls, as developed by British born Indian architect, Laurie Baker, was first an attempt towards low cost housing programs, using fewer bricks (thus less mortar), and the openings in the arrangement serving as windows (see Fig. 2) (Patti 2018). The notion is gaining more popularity with architects and buildings from the same region. Now because daily temperature range in the hot-humid tropics is small, thermal mass is not desirable (Hocine *et al*. 2010). Consequently, the inner skin can be light weight material.

A practical application of jali is seen in the Boys Hostel Block project in Gurugram, India, by Zero Energy Design Lab. The outer bricks of the jali wall were staggered and rotated for improved daylight and enhanced shading according to patterns in Fig. 3(a). Their analysis revealed that the jali façade reduced direct and diffused radiations by as much as 70% (reducing the heat gain in spaces behind the wall) while day light levels were not below 250lx as shown in Fig. 3(b).

4.1.2.2 Materials and courtyards

Another design strategy for indoor environment control is through a building fabric and courtyards. Tests conducted by Fathy (1986) on experimental buildings using mud brick walls and prefabricated concrete panel walls revealed that air temperature fluctuation inside the mud brick model did not exceed 2°C during 24-hour period, varying from 21-23°C, which is within the identified range for human comfort, shown in Fig. 4(a). However, recorded maximum air temperature in the prefabricated model reached 36°C, that is 13°C higher than the mud brick model and 9°C higher than the outdoor temperature value, see Fig. 4(b).

Also, bricks do not retain heat. When designed with openings as in jali and combined with open courtyards, the potential of natural ventilation can be maximized. Indeed, in tropical climates, courtyards function as openings to capture air to ventilate the building (Mohammad *et al*. 2012) as well as to allow natural light.

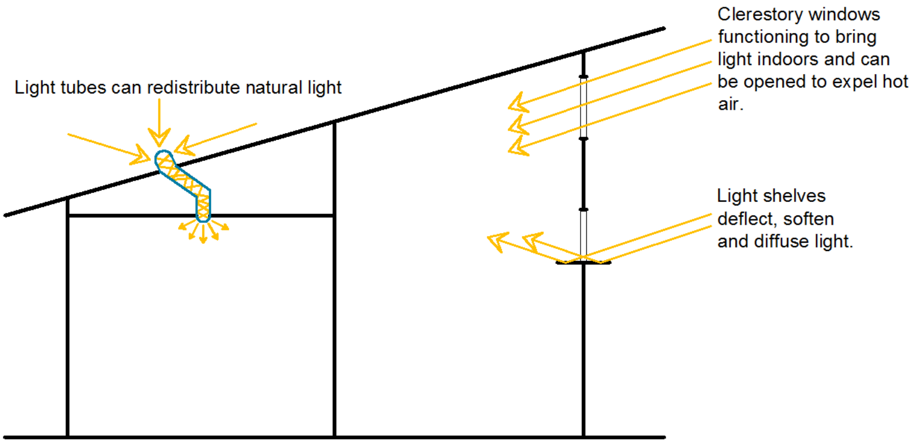


Fig. 5 Operation of clerestory windows, light shelves and light tubes (adapted from John C. Clem, Building a Better, Greener Home, Cairns Regional Council 2011)

4.1.2.3 Clerestory windows, light shelves and light tubes

Lighting is an important component of the indoor environment. Natural lighting has been proven to have significant impacts on the productivity of building occupants. Windows allow for the entry of daylight into buildings, however, only up to 4-5meters (Cairns Regional Council 2011). The extent of this can be enhanced by clerestory windows, light shelves, and light tubes, allowing natural light to passively penetrate deeper into buildings or be redirected to spaces without windows. By definition, clerestory windows are high, vertically placed windows which are a good source of diffuse light; they can also function to expel hot air in the tropics. With light shelves, the direction of natural light can be deflected onto ceilings. The ceiling then (re)distributes the light further indoors. Light shelves provide the advantage of shifting the light from windows so it can come from a more overhead direction, avoiding direct contact with interior spaces, and improving the quality of illumination. They distribute day lighting only from the portion of the window above the light shelf and thus, should not be shaded by outside objects. The bottom part can, however, have shading devices to prevent glare (Wulfinghoff 1999). With light tubes, daylight can be transported or redistributed into areas not serviced by windows. Also called sun pipes, sun scopes, solar light pipes, sky lights or daylight pipes, it basically consists of a dome (which collects and refracts day light - usually from the roof), a tube (lined with highly reflective material to minimize loss as the light travels), and a diffuser (that spreads light into the desired room). Light tubes, compared to conventional skylights, offer more flexibility for use in inner rooms with no contact with the external environment, and according to Far Eastern Economic Review (2003) can redistribute up to 98% of light received (see Fig. 5).

4.2 Smart materials

The business of architecture has been described by Salvadori (1980), as the successful union of art and technology, established by means of materials (Le Corbusier 1931). Materials play an important role in the actualization of any architecture, the choice of which had hitherto been influenced by local climate, availability, and cost. With advances in construction methods, the industrialization of the building process, and the invention of mechanical air conditioning systems, it is now possible to have buildings that are lighter, cheaper, and completely detached from the limitations imposed by the local climate (Duggal 2008, Salvadori 1980). In fact, this made it possible for buildings to be ‘transplanted’ from the temperate to the tropical regions without recourse to the changed climatic context (Joo-Hwa and Boon Lay 2006), and cities around the world to have the same (architectural) identity as their more prosperous counterparts. Indeed, with the structure of new buildings achieved through steel or concrete frames, most of the wall surfaces could be made with glass panels. Any issues around comfort are quickly dismissed because the control of the indoor environment is now possible, supported also by the notion that maintaining indoor conditions at a fixed flat-line value, guarantees satisfaction and comfort; this however has been found to be false with as much as 43% of building occupants expressing dissatisfaction with HVAC systems, and 56-86% of government workers in Europe and the US regarding it as a problem, not to mention the energy required to keep them running (Francis and Cristian 2006) and the ground space they occupy - a minimum of 4% of each floor’s gross area is recommended for air-handling equipment alone in museum buildings (Smithsonian Institution 2012).

In more recent times, after the energy crisis of the 1970s, and the global call for energy efficiency, the notion of building performance is gaining popularity (Hugo 2012) and material choices are now based on performance, multiple functions, (Edward 2005) and responsiveness rather than their aesthetic appeal (Chris 2013). Material choice can reduce replacement cycle, and eliminate associated (re)installation and energy costs (Government of South Australia 2017). Indeed, in exploring the notion of new materials, energy management is now a major consideration, so as to ensure significant savings (Laszlo *et al*. 2012). These ‘new’ materials are expected to have one to several properties that can be significantly altered in a controlled manner in response to an external stimulus, such as light, temperature, moisture, electric or magnetic fields (Xu 2016), and are known as smart materials. Described by Ikechukwu and Moses (2019) as exceptional substances that exhibit quick responses to their environment, smart materials generally manifest noticeable physical change when there is a difference in the physical or chemical conditions of their immediate surroundings (Christopher 2002). In classifying smart materials, Addington and Schodek (2002) identify four attributes that distinguish them from the regular architecture materials:

• property change (materials that can change their chemical, thermal, mechanical, magnetic, optical, or electrical properties in response to change in environmental conditions);

• energy exchange (materials that can convert received or input energy into another form);

• size/location (materials that have small size and direct action);

• reversibility (materials that can reverse input and output energy forms).

These characteristics of smart materials can be exploited, or adopted in systems to optimize building allostasis, maintaining comfortable indoor environment conditions without mechanical support.

An application of the property change smart material can be found in adaptive glazing which can reduce energy costs from heating, cooling, and lighting by as much as 50% in commercial buildings through the use of electrochromic, thermochromic or thermotropic smart windows. The principle is that of change in transmittance of light as a function of temperature - restricting transmission of infrared radiation (or heat) when temperature is high (Bell *et al*. 2002).

For humidity, a study by Emile (2002) of earth ceramics revealed that they possess excellent thermal insulation and (self) humidity regulation properties. Original nano-pores of soil used in earth ceramics remain after solidification, and thus are effective in regulating the indoor

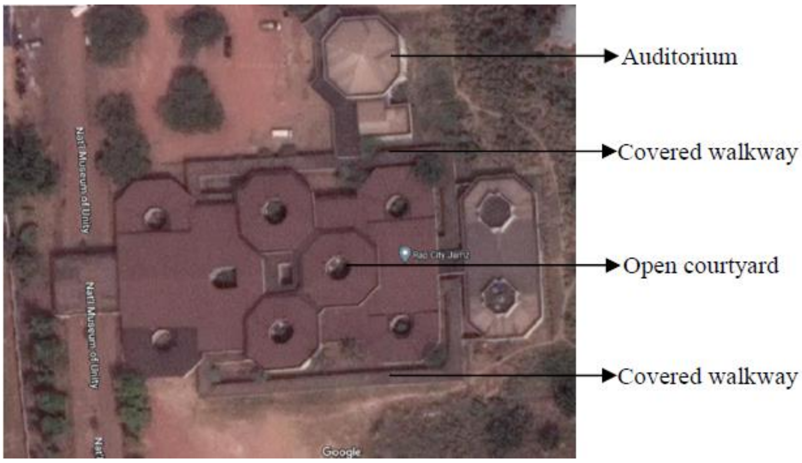


Fig. 6 Google image of the National Museum of Unity, Enugu State, Nigeria (Google Earth 2021)

environment of buildings in the hot-humid tropics where humidity range for comfort is revealed to be between 40% to 65%. The earth ceramic tiles were used as the flooring material in the living room of an apartment. Changes in temperature and humidity measured against a reference apartment in the same complex, but with acrylic carpet flooring, while other factors remained. Results revealed that the room with earth ceramic flooring exhibited very stable temperature variation. Additionally, the humidity in room with earth ceramic tiles was unaffected by the outdoor environmental conditions. The temperature and humidity in the earth ceramic floor apartment were within the range 15°C to 18°C and 40% to 50%, respectively, indicating that extremely stable and comfortable living indoor environment can be obtained by the use of earth ceramics. The measurements were continued for a year, and it was found that, compared to the reference apartment, the variations of temperature and humidity were small throughout the year in the earth ceramic floor apartment. In particular, the humidity was within the 40% to 70% RH range, which is the normal range of comfort for humans, making the use of humidifiers or dehumidifiers unnecessary.

5. Museum buildings in hot-humid tropical climate of Nigeria

5.1 National Museum of Unity Enugu, Enugu State, Nigeria

The polygonal shaped museum accommodates four octagonal shaped galleries with courtyards in each, as well as other support spaces - offices, storage, preservation, an outdoor auditorium, etc, all horizontally distributed across one floor. Each gallery has an open courtyard, the walls of which provide display surfaces. Some artefacts are displayed in glass boxes, while others are left open. The galleries have sufficient headroom with clerestory windows which are permanently shut. No other windows were noticed. Thus, no means of air exchange or passive ventilation through stack effect. Around the museum building are covered walkways with courtyards which shield the walls of the galleries from direct solar radiation in addition to providing access to other areas of the museum (see Fig. 6). Also in the galleries are fans and air conditioning units which are turned off as soon as visitors exit the building. The indoor temperature in the galleries is maintained

(a) Auditorium (outdoor view) (b) Auditorium (indoor view)

Fig. 7 Auditorium area of National Museum of Unity, Enugu, Nigeria (authors)

(a) Museum gallery (outdoor) (b) Museum gallery (indoor)

Fig. 8 National Museum of Unity, Edo State, Nigeria Source (a)-authors, (b)-tripadvisor.com

with air conditioning units, regardless of outdoor conditions, and only when visitors are present. Ventilation cement blocks were observed in the auditorium, but behind shut windows. While they appear effective in regulating solar intensity, their ventilation potentials are not harnessed as shown in Figs. 7(a) and 7(b). The museum building is sited 215 meters from the major access road so as to reduce dust and other particulates build-up from vehicular movement.

5.2 National Museum Benin City, Edo State, Nigeria

The circular shaped museum building consists of the administrative offices with the museum library, and the galleries. The circular galleries have a courtyard at the middle, providing more wall surface for artefact display and passive ventilation. Most of the artefacts are displayed in glass boxes. Only clerestory windows are used on the ground floor gallery to allow passive lighting. They are shielded from direct solar radiation by the cantilevered upper floor. 150mm wide lover windows are used to minimize passive light, as well as ventilate the upper floor galleries. These louver windows are sometimes opened perhaps to regulate the indoor environment conditions, especially when there are no visitors in the museum, but are hardly effective because they are covered on the inside with curtains. The indoor temperature is maintained regardless of outdoor conditions using mechanical HVAC systems. Some artefacts are displayed in glass boxes. Electric luminaries are used for effect as well as for navigation. No treatment is given to the walls of the upper floor galleries. They are exposed to direct solar radiation and rain from the outside, see Fig. 8(a)-(b). The building is located away from vehicular parking spaces as well, to reduce dust and other particulates build-up from vehicular movement.

6. Conclusions: A case towards climate responsible popular architecture

Several climatic conditions adversely affect the life span of museum artefacts, accelerating their deterioration. These have been identified to include direct light, temperature, and relative humidity changes as well as air pollution. Although these can be passively controlled, standards for indoor environment control are strictly followed using mechanical HVAC systems to maintain temperature and relative humidity, while light and air pollution are controlled by avoiding openings that bring in natural light and outdoor air. These practices have not only been shown to be ineffective, but also substantially increase energy demands and operational costs, as well as harm the environment, exacerbating climate change, because of energy used to make the space comfortable.

The current study through review of existing literature and visits to two museum buildings in hot-humid tropical climate of Nigeria, identified a gap between research and practice. While research identifies wide sustainable ranges for the indoor environment variables of temperature, relative humidity, light, and air pollution, standards of practice specify a flat-line, maintained through mechanical systems, describing them as essential. Even when appropriate and safe micro-climatic conditions are provided for sensitive museum artefacts in boxes, mechanical air conditioning systems remain necessary for visitor comfort because almost no consideration is given to natural ventilation. In fact, an identifying factor for most museum buildings, regardless of location, is the almost total absence of windows, due to the thinking that all external air and light is dangerous to museum artefacts and that mechanical systems constitute the best indoor environment control and occupant comfort tools. It is this thinking that allows for design transplants and indoor environment practice referrals without regard to changed climatic context. Standards are straightaway adopted, instead of adapted to suit particular local conditions, contributing to the dependence on mechanical systems for visitor comfort. Low regard is given to the rather unknown *popular architecture* as opposed to *representative architecture*, the latter crammed with theoretical aesthetic concerns, and would rather create artificial environments than be integrated with the local climatic context. Representative architecture is usually undertaken by well-known architects, found in large office buildings, clad in glass as a symbol of modernity and prosperity, or in some museum buildings reminiscent of crushed tin cans or huge concrete lumps, with the casing separating them from the outside making it necessary to use air conditioning all year round and artificial lighting during the day even when outside conditions are favorable and pleasant. Popular architecture on the other hand is performed by a people as a direct response to their needs and values, shows greater respect for the local environment and takes the constraints imposed by the local climate fully into account (Helena 1988). Indeed, it is the growing preference today among designers, allowing a more holistic approach to design, maximizing the use of passive design strategies to minimize or eliminate dependence on active systems to control the indoor environment and reducing the operational costs of (museum) buildings.

Other strategies as discussed, have been shown to be effective in reducing the extremes of temperature as well as relative humidity which vastly accelerate biological activity. Measures to ventilate naturally can be achieved using (brick) jali screens as outer walls, allowing various levels of openings on the main (inner) wall: windows, although sources of glare and uncontrolled light, can also provide the most energy efficient lighting using smart principles which can also greatly reduce heat build-up caused by artificial lighting: light shelves and light tubes can also be used to redirect natural light: smart materials considerations also provide self-monitoring and self-regulating properties for the control of the indoor environment without mechanical support. It is also important to understand and differentiate the notion of 'smart' and 'intelligence' in built environment discourse. While both basically involve response to external environmental stimuli, the latter consists of an array of often complex protocols requiring computer systems and networks which also require energy.

Local climatic conditions are also of great importance in the design of buildings. Building energy demands in both the long and short term are affected by how well the local climatic was considered at the design stage.

Museums are significant buildings and works of art of themselves, first attracting visitors before they proceed indoors. However, while they install awe, their overall impact on the visitor and the environment must also be considered. Indeed, review and discussions on these buildings must go beyond their perceived historical, cultural, and aesthetic appeal to include their functionality, environmental control and energy saving measures.

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