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The devolution of thermal resilience in residential houses in Khartoum

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Introduction

Context

Sudan is a Sub-Saharan developing country, which has witnessed an economic oil boom that led to increased air-conditioning (AC) reliance. AC consumes vast amounts of energy to cool buildings, which contributes to global warming and climate change (Rodrigueza and D'Alessandrob, 2019), while the increased temperatures further encourage AC use, creating a vicious cycle. The total number of AC units imported in Sudan grew from 12,000 units in 2004 to 150,000 in 2019 (CTC group records). The hot and dry summers last for nine months with temperatures reaching 45°C (Perry, 1991). The AC increase is happening mainly in Khartoum, the capital, which consumes 70% of the country's electric production even though its residents make up only 14% of the population (Statistics, 2008). The energy deficit between supply and demand is growing and the country started importing electricity from Ethiopia in 2012 (Rabah et al., 2016). The areas connected to the electricity grid suffer from a 40% electricity shortage, which forces the National Authority of Electricity to schedule regular power cuts especially in the summer (Ghandour, 2016).

The increase started slowly since the 1970s, increasing pace in the last 15 years. To reduce this dependency and improve thermal resilience, it is crucial to increase the environmental performance of buildings and encourage adaptive thermal comfort (Moore et al., 2017). This will require focusing on both the occupant and the building, both of which have changed with the rise of modernized living and increased urbanism/densification in Khartoum. With a single thermal comfort study ever conducted in Sudan in 2000 (Rodrigueza and D'Alessandrob, 2019), there is limited information on the current thermal performance in Sudanese houses and if poor performance is the main driver behind this accelerated increase of AC use. This study addresses this gap using a combined qualitative and quantitative approach to understand the thermal comfort issues within the wider socioeconomic context. Furthermore, it explores the evolution of adaptive behaviour, taking a historic perspective. It retraces the economic and social factors driving AC usage and how it affects the role of adaptive behaviour amongst occupants. This holistic approach differs from most current thermal comfort studies

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which focus on systematically calculating the limits of thermal comfort, performance of certain typologies or targeting specific adaptive behaviours such as window opening.

Literature review

The evolution of the Sudanese home

'Sudanese society, like other societies, is slowly changing, and the social concepts and standards of its members are gradually assuming new forms' (Fawzi, 1954). Up until the Turkish occupation in 1821, Sudan was composed of villages and small market towns. The traditional rural house was composed of scattered rooms, rakoobas (a straw roof veranda) and courtyards (Elias, 1970). Several researchers documented how people in courtyard houses migrated within the house throughout the day (Ahmed, 1978; Elias, 1970; Osman, 2014; Osman and Suliman, 1996). Figure 11.1 shows which spaces were used at different times of a summer day in a Sudanese courtyard house (Ahmed, 1978). The occupants would spend their early mornings in the shaded part of the yard and move to the veranda as it got hotter. During the peak heat time at noon, they would move their activities indoors. This often included taking a siesta, common adaptive behaviour in hot climates. This was the only time of day where indoors was more comfortable than outdoors due to the thick mud walls high thermal mass. By the afternoon, they would go back to the veranda. In the evenings, they would prepare the yard to sleep in. This included spraying the yard to cool it, bringing the mattresses out, preparing the evening tea, etc. These actions are labour-intensive, but the extended family structure provided ample opportunity to socialize while doing them. As the yard was central to all activities, it was usually heavily vegetated. During the winter, more hours are spent indoors, especially at night when the warm thermal mass becomes desirable.

It thus becomes evident that the traditional household had two interdependent components: the house providing the thermal variety and the lifestyle existing because of it.

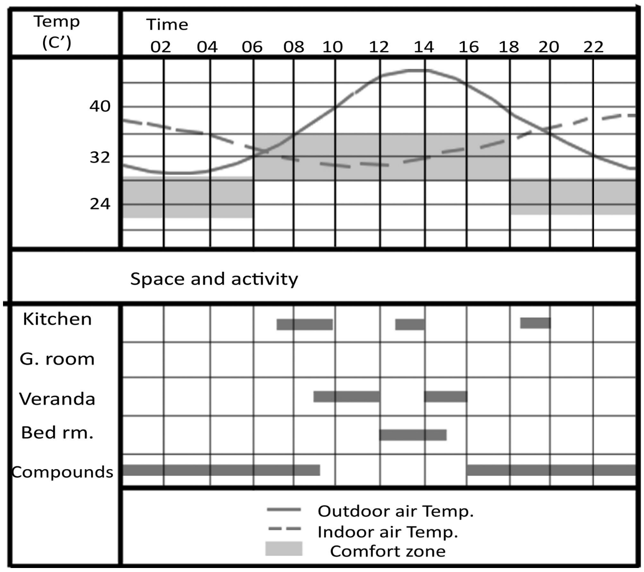

Figure 11.1 Time spent in different spaces in a courtyard house

Activities were preformed where it was most comfortable, rather than in an assigned place. For example, cooking could happen in the kitchen, veranda, yard or indoors. A key challenge is that the traditional house typology requires a relatively large building footprint to meet the occupants' needs, abundant in rural areas and scarce in cities. To respond to this challenge, in 1949, the government conducted a social survey, which led to 'the institutional house' design (Osman and Suliman, 1996). This design met the occupants need for privacy and thermal variety within $200m^2$. The two opposite facing rooms created two separate courtyards, allowing occupants to use the yards without being interrupted by the frequent guests. The verandas replaced the rakoobas, which needed frequent repair. This house can be considered a transitional phase, where the building had changed, but the occupant lifestyle had not.

The Arab oil boom in the 1970s attracted many Sudanese, who later returned to Sudan carrying the modern building ideals common in the Arabian gulf (Elkhier, 2014), e.g. modern Mediterranean style villas rather than vernacular one-storey veranda houses (Bashier, 2008). This led to a change in people's lifestyles and behaviours, as people no longer spend most of their time outdoors as documented by Merghani (2006) and Osman and Suliman (2005). The veranda became the 'hall' which later evolved to the 'living-room'. With each stage, the spaces became more enclosed, until the house became one compact unit. As a result, spaces now had fixed functions, such as sleeping and socializing. This reduces the occupants' ability to perform activities where it is most comfortable. In addition, the kitchen and bathroom became part of the main building, while concrete, glass and air-conditioning became common (Osman, 2016).

Thermal resilience

ACs have been added to both traditional and modern buildings in Sudan since the late 1960s. The introduction of ACs impacts occupants, as users acquire a higher expectation of their thermal environment which consequently decreases their reliance on adaptive behaviours (De Vecchi et al., 2012). Additionally, ACs reduce the range of temperatures the occupant can withstand. The human body has a robust system to adjust to the surrounding by changing the blood flow, changing the occupant's behaviour, etc. (Humphreys et al., 2007). The more thermal variety a person is exposed to, the better their body can adjust quickly. Occupants in air-conditioned buildings spend most of their time in a highly controlled environment, while in naturally ventilated (NV) buildings, they are exposed to a wider range of temperatures. This is why in areas with large seasonal thermal differences, residents tend to have a higher thermal comfort range, e.g. Jaipur, India (Dhaka et al., 2013), or Japan (Rijal et al., 2019). It is also why occupants in mixed-mode buildings tolerate a wider range of temperatures than in AC buildings and a smaller range than in NV buildings (Karyano et al., 2015; Manu et al., 2016).

Human resilience is the occupants' ability to withstand thermal stress, to cope once it peaks and their capacity to recover once the stressor is removed. This study theorized that the combination of introducing AC compounded with the loss of thermal variety in Sudanese houses would therefore reduce human resilience which is explored in houses that have experienced these changes, i.e. traditional houses.

Methodology

Six houses were each fitted with Tinytag and Hoboware temperature/RH dataloggers (−25 to +85°C, ±0.01°C), one in a conditioned and a second in an unconditioned space, installed

Table 11.1 Details of the monitored buildings

	Building features				*Occupant details*		
	Typology	*Wall type*	*Roof type*	*No. of floors*	*AC type*	*Family type*	*No. of occupants*
H1	Traditional courtyard	Composite brick/ adobe mix	Traditional wood/straw /earth mix	1	Evaporative cooler	Extended	9
H2	Modern apartment building/villa	20cm brick	Reinforced concrete (RC)	3	Split unit	Extended	6
H3	Modern apartment building	30cm brick	Reinforced concrete (RC)	2	Split unit	Nuclear	3
H4	Modern apartment building	20cm concrete block	Reinforced concrete (RC)	2	Split unit	Nuclear	2
H5	Traditional courtyard	40cm brick	Corrugated metal with false ceiling	1	Evaporative cooler	Nuclear	4
H6	Traditional courtyard	50cm stone in H6-B, 20cm Brick in H6-L	Corrugated metal with false ceiling	1	Evaporative cooler	Extended	6

Note: Nuclear families are composed of parents with their children, while extended families include grandparents or lodgers or multiple nuclear families.

at 1.5m high from the floor, recording every 15 minutes. Following a one-week pilot study (Elsherif et al., 2020), one-month long surveys were conducted in 2019 (5/5/19–30/5/19 for H1–H3; 1/6/19–1/7/19 for houses H4–H6). An external datalogger was placed in the balcony of the first floor of H3. The sampled houses were chosen based on logistical and security preferences. The occupants recorded their AC use, except for H5, who lost their log. All six houses have ceiling fans in every habitable room. Interviews were conducted to understand the occupants' experience and usage patterns. Follow-up interviews and building surveys were conducted in H5 and H6 to explore the evolution of the houses through time looking at the behaviour, physical fabric and technology, to map the progression of thermal resilience.

H1, H5 and H6 are single-storey courtyard houses with families from the lower middle class, relying on evaporative coolers as shown in Table 11.1. Evaporative coolers use a fan to pump air through wet straw to cool dry hot air by increasing its humidity. H2, H3 and H4 are modern houses with families from the upper middle class, using the split units. AC split units use refrigerants and have a connected outdoor and indoor unit. Split units consume 1.29–2.1 kWh, while evaporative coolers consume only 0.09–0.18 kWh. H2, H3 and H4 have a ground floor for the main family and an upper floor for their children, except for H4 with two apartments on the first, one rented and the other for the daughter. The samples are grouped into a 'traditional' and 'modern' category for the discussion. Different construction types were also chosen to identify potential variations in thermal comfort.

Results and analysis

Thermal performance of buildings

Thermal comfort in the traditional group

The occupants in H1 have a budget that limits their use of the evaporative cooler to nine hours. They chose to use the AC during the day and sleep outdoors at night. There are three users occupying the living-room, who are at home during different times of the day, reflected in frequent turning on/off of the AC in H1 as they enter and leave the room (Figure 11.2). These factors resulted in an irregular temperature pattern within the space. It took eight hours for the air-conditioned living-room to become as hot as the unconditioned bedroom when the AC was turned off on 17th of May. The occupants complained that the bedroom is too hot, so they only use it for storage, with daytime temperatures in the unconditioned bedroom 32–41°C.

Occupants in H5 positioned the evaporative cooler opposite to the door and kept it open, to use it for both spaces. This is reflected in the readings with both spaces following the same pattern, with the bedroom being colder as the cooler was located there. This compromised the ability to use the unconditioned space as a reference. The occupant said that the AC was usually turned on from midnight till 18:00 or 21:00 the following day and only turned off for six to eight hours/day. As they lost their AC log, the AC time plotted is tentatively based on their disclosure. Temperatures ranged from 26.6–34.8°C in the bedroom to 28–37°C in the living-room. The occupants spend most of their time in the living-room as the bedroom was occasionally too humid.

In H6, both living-room and bedroom have evaporative coolers. The bedroom is made of stone and the living-room of 20cm thick brick. Temperatures ranged between 25.1–33.2°C in the bedroom and 24.3–36.1°C in the living-room. The readings show that the spaces share similar thermal patterns despite the difference in construction with the mean temperature being 29.2°C in the bedroom and 28.9°C in the living-room. The AC was turned on average for 6 and 12 hours/day in the bedroom and living-room, respectively, which coincides with observations that the living-room is used both day and night while the bedroom only at night.

All three houses left the door open and frequently turned the AC on/off to release moisture built up from the evaporative coolers. Turning on the AC cooled the spaces gradually, reaching a 6K temperature difference in six hours, while when turned off the temperature increase was slow, which could be attributed to the moist air. The conditioned space in H1 is bigger than H5 and H6 and used for fewer hours, hence its lower humidity. Another reason for the gradual drop was the smaller reduction in temperature, compared to the outdoors, from the evaporative cooler. The smaller temperature difference (ΔT) means that the rate of heat entering the building is less which slows the internal temperature rise. When the AC was left on all day (e.g. in H6, 19th May), the temperature variation followed the external temperature rather than keep declining with prolonged use. H1 used the AC during the day, while H5 and H6 used it all day when at home. Only H1 used the yard at night to sleep due to economic restrictions. H5 used to always spend their evenings and nights outdoors to socialize and sleep when the multi-generation family lived in the house. However, since modern life dictated each nuclear family to move to a separate house, only four occupants were left, with no longer the need to sleep outdoors. H6 does not use the yard even during power cuts because a high-rise building built recently nearby invades their privacy. H5 and H6 emphasize the impact of social drivers on environmental decisions.

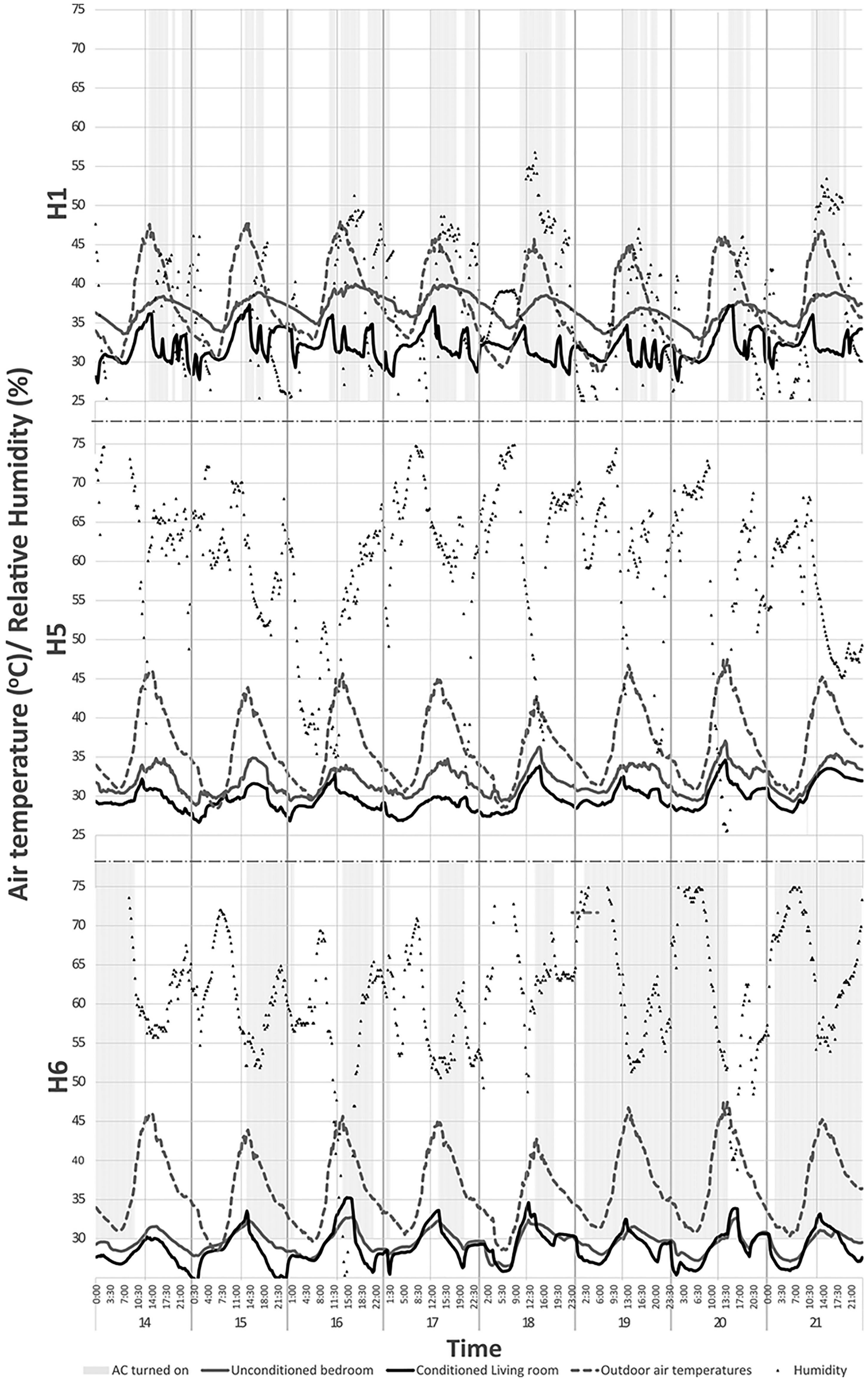

Figure 11.2 Air temperature and relative humidity variations for H1, H5 and H6 in a sample of 8 days

Thermal comfort in the modern group

The occupants in H2 turned on the AC and fan whenever they were in the bedroom, on average 14 hours/day. The set-point was 27°C which would explain the long operational hours. This kept the indoor temperatures between 27 and 33°C, lower than the living-room 35–37°C.

The occupant in H3 turned on the split unit at the same time every night, 0:00–8:00, reflected in the regular pattern depicted. The living-room in H3 was the only unconditioned space where occupants were satisfied with just a fan, with temperatures ranging between 31 and 35.8°C. This is in agreement with Nicol (1974) showing the increased air rate improving thermal comfort, for air temperatures at 31–40°C.

However, a similar range to H3 in the H2 living-room was considered uncomfortable. Such satisfaction is probably because the room in H3 is used only for guests in the evening and not for extended T.V. hours like H2. Temperatures ranged between 24°C and 35.4°C in the bedroom, where the split unit AC set-point is 25°C. The occupants in this house expressed general satisfaction with their house thermal performance throughout the year.

In H4, the occupants used the lowest possible 18°C set-point. Temperatures ranged from 22.1 to 40.7°C in the bedroom and from 30.5 to 40.2°C in the living-room. The occupants have mentioned that guests always complain that the living-room is too hot. During the weekend, 15th June, the AC was turned on for 22 hours because of how fast the room heats up.

Focusing on the temperature drops, Figure 11.3 shows that the split units achieved up to 16K temperature difference very quickly. However, H4 kept that coolth for only 5 hours, while H3 maintained it for 16 hours before the temperatures reached the same as the unconditioned spaces. This highlights the impact of the building fabric. Turning off the split units had a stronger immediate impact on internal temperature rise compared to evaporative coolers. This is evident in the sharp temperature increase in all three houses in the first hour after the AC is turned off. This could be due to the higher temperature difference the split units reach, compared to evaporative coolers which speed up the heat infiltration rates. This means that the lower the set-point temperature of the split unit, the more energy it must consume, not only to cool the space, but also to mask the increased heat infiltration caused by the bigger temperature difference.

All three unconditioned living-rooms in the modern group were rarely used and none of the occupants use the yard. H2 complained that it was due to privacy issues from the surrounding multi-storey buildings. H3 commented that they live a modern lifestyle that does not include staying outdoors and they felt that their house was cool even during power cuts. H4 did not have access to the yard, as they are renting, unlike the other tenant on the floor who is related to the family. H5 explained that because of this, during power cuts, she only has access to a small balcony and frequently stays in the car to use the AC, because her baby cannot tolerate the 40°C temperature indoors. This highlights the impact of social norms on the building and emphasizes the difference between apartment houses that are built as a vertical extension for the same family, compared to commercial apartment houses where tenants are not related.

Temperature distribution throughout the monitoring period

To compare the performance of the six houses, Figure 11.4(a) summarizes the temperatures experienced in these spaces, while Figure 11.4(b) shows the distribution of temperature

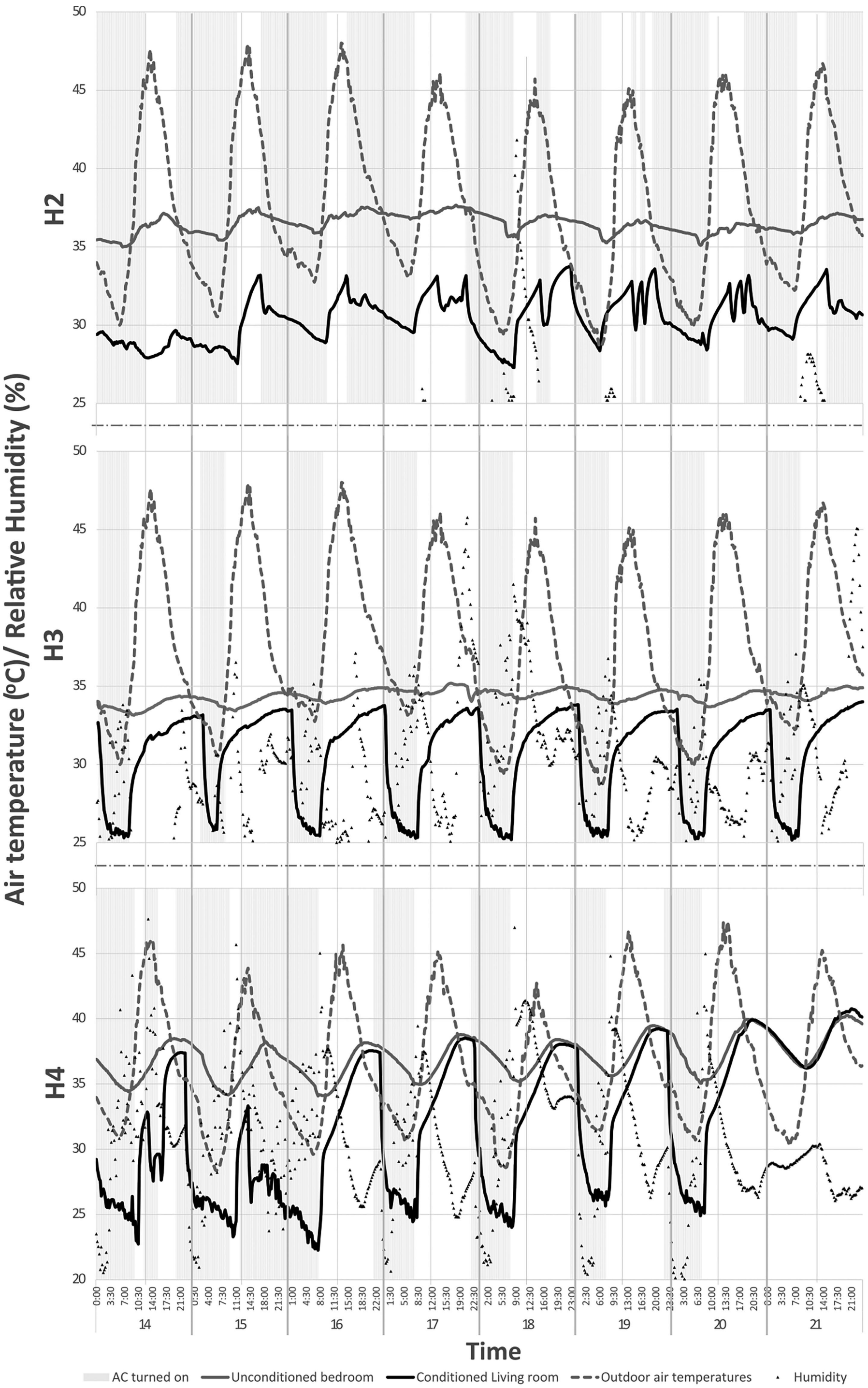

Figure 11.3 Air temperature and relative humidity variations for H3, H3 and H4 in a sample of 8 days

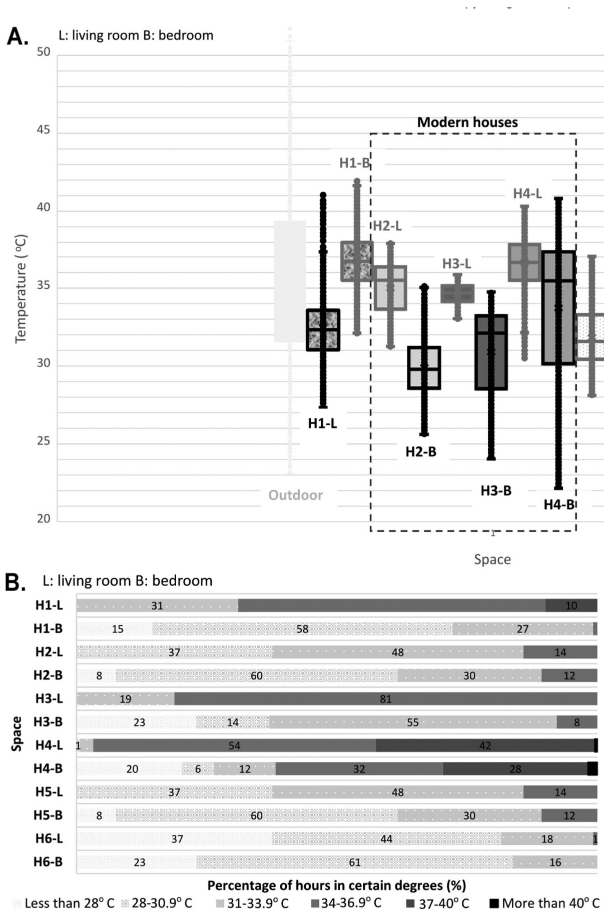

Figure 11.4 A: Temperature distribution in the 6 monitored houses; the black lines are conditioned spaces, while the lighter lines are unconditioned spaces. The pale grey is the outdoor range. B: Temperature distribution in the 6 monitored houses, the patterned bars are within the comfort range (up to 34°C) and the solid colours are outside the comfort range

ranges within the spaces. The mean temperature across NV spaces across all houses was above 34.6°C, the reason they are mostly unused. The exception was the living-room H5-L, which benefited from the cool air escaping from the bedroom. The concrete block H4 had the poorest performance with a wide range of temperatures (22.1–40.7°C) (Figure 11.4(a)). Figure 11.4(b) confirms this as only 38.2% of readings were below 34°C in the bedroom H4-B and 3.2% in H4-L. In Figure 4(a), the best-performing spaces were in H6, with mean temperatures 28.9°C and 29.2°C in H6-B and H6-L, respectively. However, H6-B required only 6 hours to achieve this compared to the 12 hours needed by the adjacent living-room H6-L. This shows the impact of the improved fabric as H6-B has stone walls, unlike the H6-L brick walls. This improved performance is also evident in Figure 11.4(b). Both traditional houses H5 and H6 had the highest percentage of temperatures below 34°C, as the darker bars were smaller.

Adaptive thermal comfort

Indraganti et al. (2014) developed an adaptive thermal comfort model for the hot climate of South India, differentiating between comfort in NV and AC spaces. Their models are more suitable to assess the thermal comfort of the case study buildings compared to the ASHRAE-55 and EN15251 models for colder climates. The weather station in Khartoum airport was used to calculate the daily running mean during May and June. The outdoor running mean in Khartoum was higher than 34°C in both months which is higher than the range limits by Indraganti et al. To estimate occupants' thermal comfort outside these limits, the upper and lower limits provided by Indraganti et al. were extended (dotted line in Figure 11.5). When comparing with other hot climate studies, 34.8°C was the highest internal comfortable temperature recorded in Jaipur (Dhaka et al., 2015) and was used to cap the comfort zone regardless of the outdoor running mean.

Figure 11.5 highlights that only 1% of H2 living-room fell within the comfort zone followed by 6.3% for H1-bedroom and 23% for H3-L. H1-B has a standard deviation of 2.1°C compared to only 1.7°C in H2-L. This means that the internal temperatures have a greater diurnal swing, which although heats up rapidly during the day; it also cools quickly during the night. This explains why H1-B has more instances within the comfort range even though its mean temperature is higher than H2-L. H6 has been excluded as both spaces had evaporative coolers. The graph shows that 87% of the H5-L temperature distribution was in the

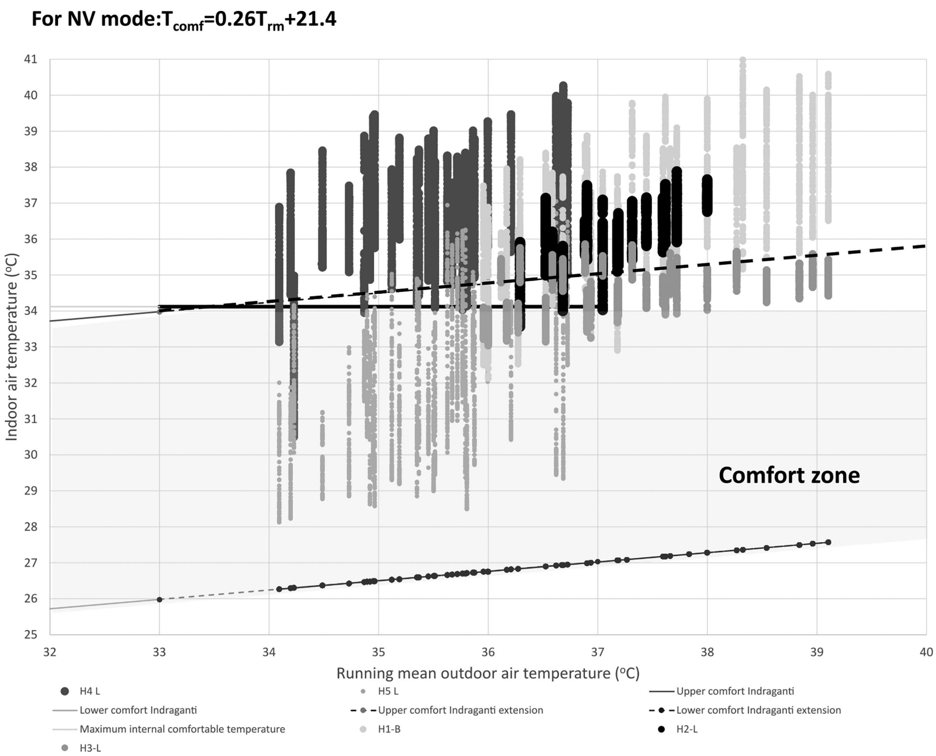

Figure 11.5 Comfort range for NV spaces in H1, H2 and H3 during May and H4 and H5 during June

extended comfort zone compared to 3.8% of H4-L. This is because the evaporative cooler in the bedroom leaks cool air into the space, not just due to the fabric.

Evaluation of AC zones using the adaptive thermal comfort method

Figure 11.6 shows that the temperature was within the comfort zone for H1-L for only 37.4% of the time, followed by 43.2% in H3-B and 81% in H2-B. H3 performed better than H2 in the NV spaces, as although they share the same roof type, the walls in H3 are 10cm thicker. H3 turns on the AC for 14 hours though, compared to just eight hours in H2 which is probably why H3 performed better in the AC zones. It could be speculated that H1 performs poorly because it is very leaky and all the cool air leaks through the windows and doors, or their evaporative cooler is not working properly. Figure 11.6 also shows that temperatures in H4 were in the comfort range for only 27.1% of the monitored period followed by 74.2% in H5, 85.5% in H6-L and 89.6% in H6-B. The absence of occupants on H4 for several days meant that the AC was off, which explains why only 27.1% of the readings are within the comfort range, but the house still performs poorly, quickly heating up when the AC was turned off.

Thermal performance discussion

Houses in Khartoum have a major overheating problem. NV spaces in all six houses were comfortable for only 1–23% of the time, which is why people used to spend a lot of their time

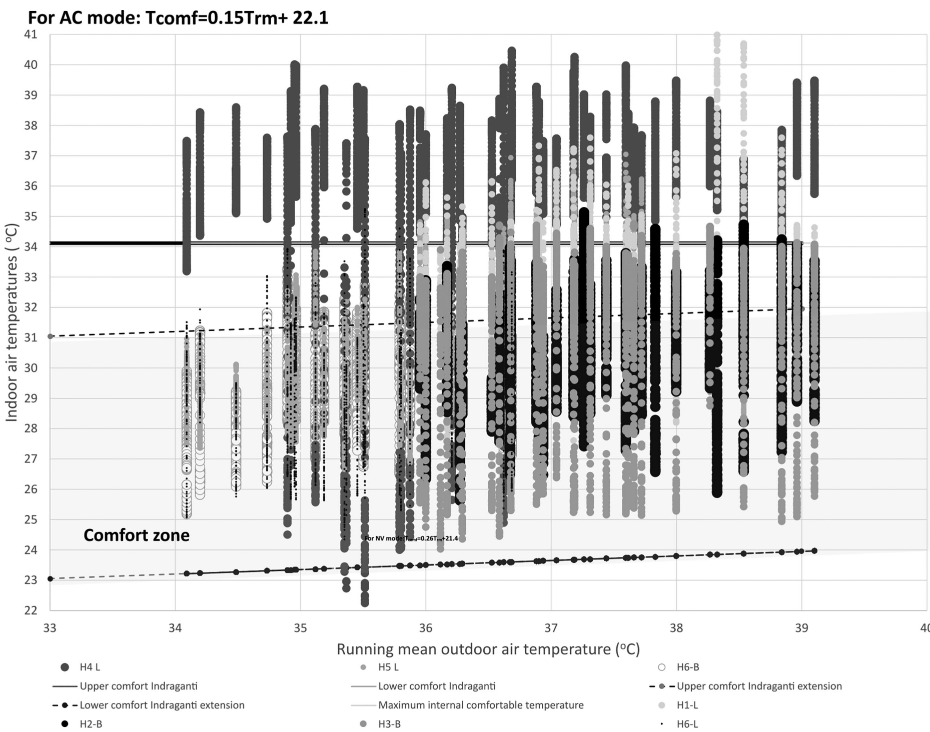

Figure 11.6 Comfort range for AC spaces in H1, H2 and H3 during May and in H4, H5 and H6 during June

outdoors, where the climate was more than comfortable than indoors. In the 1960s, ACs and fans were introduced, providing a convenient solution to the high indoor temperatures. The fans were constantly on in all six houses monitored and the windows seldom opened due to the high temperatures. The AC becomes the main variable that impacts both the building and the occupant's comfort.

AC usage created two patterns. The first emerges in well-sealed multi-storey houses with split units. The split units created a sharp drop in temperatures, followed by an increase in temperatures once the AC was turned off. This increase was gradual in brick houses and rapid in cement block houses. This emphasizes that although installing AC becomes necessary to achieve thermal comfort in Sudan, improving the fabric has a drastic impact on reducing usage time. The second pattern was prevalent in leaky courtyard houses with evaporative coolers. Evaporative coolers had to be turned on for longer periods as they cooled the spaces slowly and users kept the doors open to reduce humidity levels, while allowing the cool air to escape. This excess moisture made occupants uncomfortable in H5 and H6, despite the adapted model suggesting that spaces were comfortable 74–87% of the time. The model also shows that H1, H3 and H4 were the least comfortable, although the occupant in H3 expressing satisfaction with the space. It also shows that the stone walls in H6-B provided 85% comfortable temperatures despite only having the AC on for only six hours. Overall, the AC usage hours varied in the case studies, from 6 to 18 hours/day. They are always used at night, as in a similar study in Indonesia (Uno et al., 2017).

Traditional house evolution

The interviewees in H5 and H6 revealed that their houses have changed drastically since construction. Therefore, in-depth interviews were conducted to understand these changes and their contribution to thermal performance.

Case study H5

H5 was built in the 1990s. The family has two parents and five daughters. Before moving in, they lived in a 200m^2 plot in central Khartoum and their house was a typical institutional house. They were from a lower-middle-class family originally from Khartoum and lived a traditional lifestyle.

ORIGINAL HOUSE

In 1982, the owner and his family built the house shown in Figure 11.7(a). They built it themselves in the same institutional design of their previous house. The kitchen was separate to the main building, reducing its thermal impact. The bedrooms had a 'traditional roof' and mud walls. Having three wooden windows and a door in each room allowed for cross ventilation at night, encouraged by the mosquito mesh on them. Their veranda had a metal roof and was also closed off with mosquito mesh. The metal roof would radiate the heat to the sky at night, cooling it quickly, while the mosquito mesh allowed the breeze. These properties encouraged sleeping there, while also being a relatively cool place during the day, according to the occupants. The small built area allowed the family to have a large garden with a lawn and trees; they used to also enjoy socializing there during the evening and sleeping outdoors.

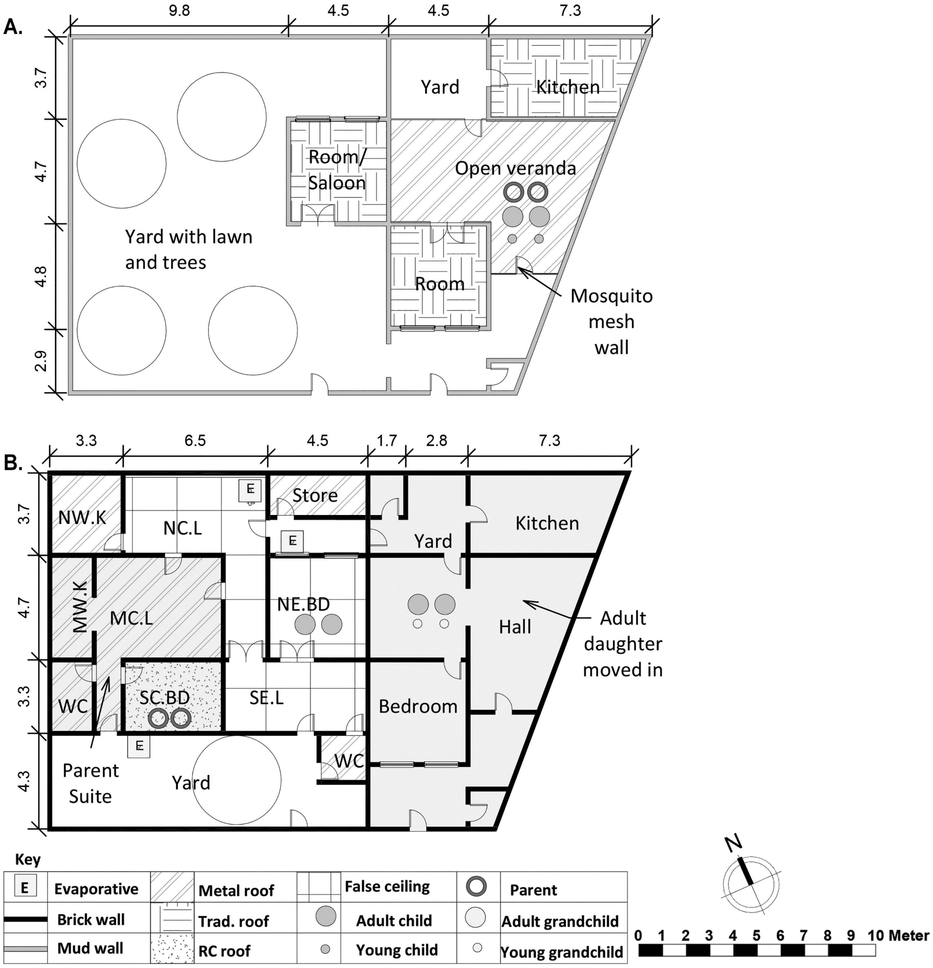

Figure 11.7 A: The plan of H5 in 1990 in its original state. B: The plan of H5 in 2020 in its current state

DRIVERS FOR CHANGE

Three factors drove change in this house: space needs, security and social change. As the family's space demands increased, so did their built area, reducing the yard area significantly and using it less. The family no longer sprays the yard, which would create a cooler microclimate. The family divided the house into two parts and moved to the left side (Figure 11.7(b)), while an adult daughter now occupies the right side. With increasing robberies since 2009 and less residents, they became fearful. Security concerns led them to change their wooden windows into metal ones, which increase overheating. It also led them to change the layout from scattered rooms to a closed unit, allowing safe internal movement between spaces. Finally, it made sleeping outdoors, a social activity, risky. As the four daughters moved out, the remaining family members had less incentive to sleep outdoors, a labour-intensive practice.

CURRENT HOUSE

The daughter turned the open veranda into two closed halls to maximize her space usage, which reduced the thermal variety in the house, as the veranda had shaded the rooms without blocking the wind flow. Brick and metal roofs replaced the traditional materials. As this was very hot, the owner initially covered it with palm leaves and bark with mud for insulation. Although it was very cool at the time, they installed a false ceiling to catch up with current housing trends. The left side (main family) expanded gradually through several phases from just one room into an entire closed building. The mother died and the father remarried, which necessitated creating a separate suite for the parents, highlighted in grey. Thus, the house functions as three separate units. The master suite has a concrete roof, because the owner aspired to replace the entire house gradually with a modern house. Another significant change was that the kitchen became internal, resulting in 45°C temperatures inside, as confirmed by thermal imaging. Windows are only opened during power cuts or occasionally during mornings, but never overnight, when mostly needed, as the mosquito mesh was removed. The daughters work during office hours, returning in the evening. Both the daughters and the parents spend the time in their rooms rather than the living-room. The owner installed three evaporative coolers. The daughters use the AC when at home, up to 18 hours, while the parents use it a little. Whenever the occupants felt hot, they opened the AC instead of using adaptive comfort methods. With the evaporative cooler raising humidity to 75%, they leave the doors open and they felt it does not cool enough.

Case study H6

ORIGINAL HOUSE

H6 was built in the 1950s. The original design was an amalgamation of the Sudanese tradition of scattered rooms and the colonial veranda (Figure 11.8(a)). The nuclear family that moved in had seven children, who are currently with their own children in an extended family setting. As the family grew, the building did as well. Each extension was built with the materials available at the time, resulting in a mismatch of different materials.

Before this house, the family lived in a traditional house with false ceiling and metal roof verandas. They were an upper-middle-class family with roots in both Khartoum and rural Sudan. They have been familiar with AC since the 1960s. They cooked mainly in the kitchen but during intense sessions cooked outdoors, a habit they still maintain. They used to sleep outdoors in some houses but not in the current location due to high rates of mosquitos. One of the houses they lived in had an evaporative cooler in each room, in a rich neighbourhood where this was the norm. The father closed the verandas in every house they moved in because he felt that Khartoum was no longer safe, although he still slept outdoors in a mosquito net.

DRIVERS FOR CHANGE

In this house, space needs, finance, security and social aspects impacted their choice of modifications when they moved in 1980 (Figure 11.8(b)). Increased space needs and financial constraints led to drastic expansion. Similar to H5, they divided the house into three units: the right wing for rent, sold the left and inhabited the middle. This expansion cost them the garden and its fruit trees. They turned the kitchen labelled 'NC.K.' into a bedroom and built

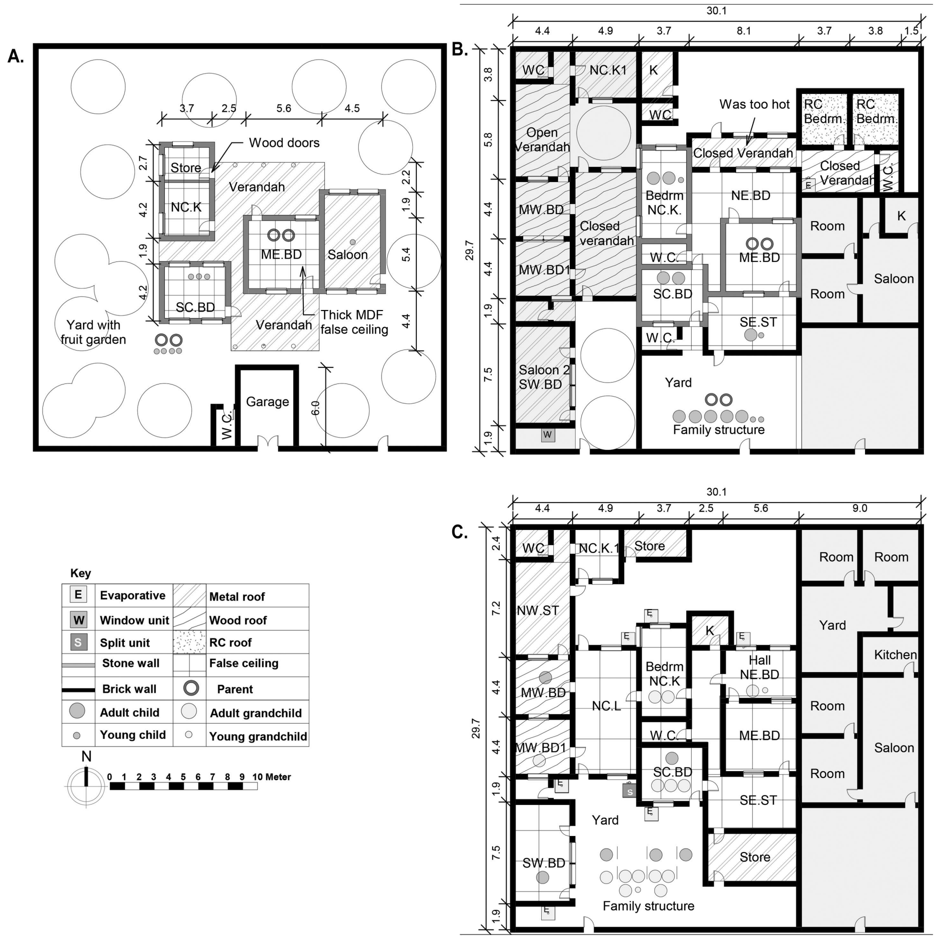

Figure 11.8 A: The plan of H6 in 1950 in its original state. B: The plan of H6 in 1980 after the family moved in. C: The plan of H6 in 2020 in its current state

a separate external kitchen to avoid internal heat gains. An open veranda near the external kitchen (NC.K1) was used for cooking and eating. It is still used that way today, despite being closed off into an internal space, extremely uncomfortable in its current state. This first expansion was done using brick as the original stone became too expensive. The new roofs were mostly metal, except four rooms in the western side built of wood, which was cheap at the time. Two concrete rooms were built in the north-east side but were very hot without AC. The owner built them because he had extra funds available and was considering gradually rebuilding the entire house in concrete, a similar aspiration to H5. For security, the owners closed off the two existing verandas into the bedrooms labelled 'NE.BD' and 'SE.ST', adding three 'closed verandahs' to link the house. A 'closed veranda' in this context is when an open veranda is closed with wall-to-wall metal windows, rather than turning it into a room. These verandas were uncomfortable and seldom used. The family installed two ACs, a window unit in the living-room (SW.BD) for guests and an evaporative cooler for the hall (NE.BD), where they spent most of their day, due to the highly social lifestyle of the family at the time.

CURRENT HOUSE

Figure 11.8(c) shows the current state of H6. The children grew up and all needed more space, so the family cancelled the rent and linked the middle and left sides. All the habitable rooms have evaporative coolers. In 2020, the occupant in the bedroom (SC.BD) added a split unit as the evaporative cooler works poorly at midday. She now alternates between the two ACs throughout the day, which has had a significant impact on the electric consumption. The family rarely spends time in communal spaces like the living-room. When the occupants return home, all go into their own rooms and turn on the ACs until they leave the following day. They rarely open the windows or curtains, unless in the kitchen to cool it. They only use the yard during power cuts, which is unpleasant as the yard does not have a mosquito mesh area. Power cuts occur daily during the summer, lasting from 3 to 12 hours day and night. Adaptive cooling techniques used by the family included taking a shower, drinking cold drinks, spraying the yard and changing into lighter clothes. However, they are only used during power cuts when mechanical cooling is unavailable, or by the older occupants who grew up without AC dependency for cooling.

Discussion

The two traditional case studies share many similarities. Both houses expanded drastically due to the expanding family needs, also driven by the need to divide the houses into different sections for rent due to economic constraints. In an urban setting with limited space, unlike a rural background where expansion would go unhindered, this reduced the yard size. The quality also diminished from well-maintained outdoor space with trees and lawns to barren ceramic tiles and small plant pots. The densely shaded microclimate combined with spraying the ground was far more effective in cooling the space than spraying the ceramic tiles exposed to the sun. These changes mean that the yards today are less inviting, contributing to reduced time spent outdoors during the evening and at night. Another similarity is how security drove both households to replace the wooden doors, close off the verandas and stop sleeping outdoors. The loss of the veranda means that even more time is spent in conditioned indoor spaces. The verandas also used to shade the interior spaces. Overall, the users' socioeconomic needs made them alter the buildings to the point they could not function environmentally as originally intended. This pattern was similar to Iranian vernacular buildings, performing well environmentally, until replaced by modern alternatives for practical and cultural reasons (Foruzanmehr and Vellinga, 2011).

Both families lost their social lifestyle and now spend more time in their bedrooms, with great energy implications as conditioning one living-room is less energy-intensive than several bedrooms. Furthermore, the availability of AC in each room diminished the need to use other adaptive behaviours and gradually, the users in both houses increased AC usage.

Traditional houses in Sudan previously provided ample opportunity for adaptive behaviour. However, the increase of internal spaces and changes in materials result in thermally intolerable during conditions for much of the day. AC reliance has replaced human resilience as a response to thermal distress. The lightweight roofs make the space intolerable during midday without an AC.

Conclusions

Traditional houses in their original socioeconomic setting encouraged adaptive thermal comfort and human resilience. However, in modern Khartoum, they can no longer function as intended due to the current lifestyle and lack of space and security to support it and have thus become dependent on AC for cooling.

Modern houses, in their current state, are also thermally uncomfortable and highly dependent on AC, especially when using concrete blocks. However, as they are less porous than the traditional houses, they require less energy from AC to cool them. They also address the current socioeconomic needs for security, space and privacy, which is why they are sought after from occupants of traditional house as well.

It is therefore critical to build affordable modern houses that reduce cooling loads and reliance on AC. Understanding the role of vernacular strategies and techniques, from the veranda to materials, and the crucial role of the courtyard and outdoor space will enable reinterpretation of the vocabulary in the modern setting to address people's changing needs and expectations for comfort in Khartoum, increasing their thermal resilience.

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