THE OPTIMISED MIXED-MODE BUILDING

COUNTERING AC RELIANCE BY RE-SYNCHRONIZING THE THERMAL ENVIRONMENT WITH OCCUPANT LIFESTYLES IN KHARTOUM

By

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In the name of Allah, the Entirely Merciful, The Especially Merciful

Abstract

The Sudanese house has had to evolve four times in the past 200 years due to changing socioeconomic conditions. It went from a spiralling compound of scattered rooms to a compact building with all the functions under one roof. This change was in order to adapt to the reduced plot sizes and changing occupant behaviour and family structure. Air conditioners have been available since the 1960s, but people relied on adaptive behaviours predominantly. Thermal migration to utilise the thermal variety in different parts of the house was an integral part of life in traditional houses. However, in recent years the increased demand of air conditioners created by the return of expats led to an increase in local production and imports, which made them also more readily available. This increased consumption has led to power cuts as the electric grid cannot cope.

This research utilised a mixed-mode method to understand the phenomenon from different contexts. Interviews supplemented the literature review of the wider context. Two modern concrete and three traditional buildings were chosen as case studies. Extensive interviews recreated the building's past, while the monitoring for a year documented the current use and internal conditions. The study found that occupants in both typologies used internal spaces for prolonged periods. The internal conditions varied throughout the day based on the thermal mass of the materials used and shading.

The study found that the thermal variety that existed in the original traditional houses can be replicated in both modern and modified traditional houses by creating zones. These zones match the user's current modern usage patterns of their house, allowing minimal need for constant movement. This solution allows the Sudanese house to synchronise with the user's daily patterns again, resulting in a reduction in electric consumption.

Acknowledgements

When I first proposed the idea of a modern building inspired by traditional Sudanese architecture, I was met with the question: Do you want us to return to living in huts? My supervisor Henrik Schoenefeldt, on the other hand, thought that it would make a great PhD. He guided me through the application processes and taught me the basics of good research, like critical thinking and analysis. His experience in historical environmental research helped balance my research's social and technical aspects. I am forever indebted to him.

My Second supervisor Marialena Nikolopoulou has been my biggest advocate. She helped me whenever I was stuck by asking me thought-provoking questions and reminding me to focus on the essential parts of my work. She has also been extremely supportive on the personal side as a fellow academic parent and a female leader in a predominantly male field.

For my fieldwork, I would like to especially thank my sister Dania, who was my de facto research assistant and my eyes on the ground. I would also like to thank my research participants, who sent me monthly updates for an entire year.

This project could not have been achieved without the generous Kent GCDC scholarship. Beth Breeze and Frank Grundig persevered against obstacles to promote and enrich the program to ensure it meets the sustainable development goals it set out to achieve.

Finally, I thank my husband, family and friends for their continued encouragement and support throughout my research years.

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Chapter 1 Introduction

1.1.Overview

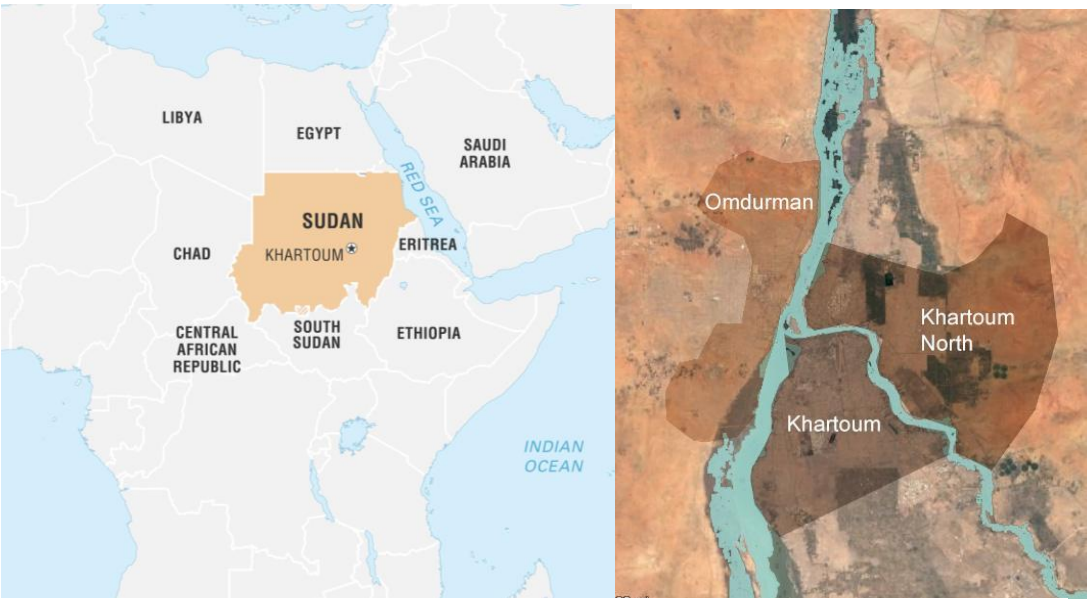


Figure 1.1 A map showing Sudan and its neighboring countries with a highlight on the three cities that compose the capital Greater Khartoum. Source: Google maps and edited by the Author

Cultural change is easier to notice when you are an outsider. As a Sudanese expat who spent every summer travelling from Saudi Arabia to visit family in the village, the Author witnessed first-hand the increased adoption of Air conditioners (ACs) over the past 20 years. These observations were confirmed through records from an AC company that showed an increase in annual imports in Sudan from just 12,000 units in 2004 to 150,000 units in 2019 (Source: CTC group records). Most of these imports are concentrated in Greater Khartoum, which is the capital of Sudan and is composed of three linked towns: Khartoum, Khartoum North and Omdurman (Figure 1.1). This could explain why the relatively small capital consumes 70% of the country's electric production even though its residents make up only 14% of the population (Statistics, 2008). As Sudan is a developing country, this high consumption leads to a 40% shortage in electricity supply. Consequently, power cuts are a daily occurrence, especially in the summer due to the use of ACs role. Sudan is a sub-Saharan country located south of Egypt. Winters (November-February) are cool and dry, with daily temperatures ranging from 5^{o}C to 25^{o}C, while the Summers (March-June) are hot and dry and can exceed 45^{o}C in their peak in late May (Perry, 1991). This issue, however, is not confined to Sudan, the high load from ACs contributes to power cuts worldwide (Lundgren-

Kownacki et al., 2018) and even impacts developed areas like California, USA. ACs contribute to 60-70% of the average electric consumption in a Sudanese home (Ministry of Energy, 2015).

In 2018, the Author conducted a pilot study to see how widespread AC adoption was and to gain preliminary insight into the causes (Elsherif et al., 2020). This was achieved through an online survey and six case studies, respectively. The study raised issues that related to both the buildings and occupants. The survey found that adaptive thermal comfort behaviours that had been an integral part of a traditional lifestyle became mainly used during power cuts, where the lack of access to an AC had forced people to adapt. Air conditioners in the survey were equally found in both traditional courtyard buildings and modern concrete-framed buildings, suggesting that the increase impacts both typologies. This indicator showed that the phenomenon could be related to overall change, not just the circumstances of specific typologies. The thermal comfort problem also extended to both typologies. The case study found that all the naturally ventilated spaces were uncomfortable and rarely used. However, the performance of airconditioned spaces varied depending on the building fabric. This explained why the survey indicated that only 13% were happy with their environment, while the majority (85%) preferred if it was cooler. Another possible factor was the rise in expectations. Although a 2000 study in Sudanese courtyard houses found that the comfortable summer temperature was 30.9ºC (Merghani & Hall, 2001), only 18.9% of users set the AC at the recommended temperature of 25ºC or more. The monthly consumption of the case study houses was between 447-2283 kWh, which is significantly higher than the Sub-Saharan Africa average of 50-100kWh per month (The world bank, 2019).

The current consumption rates are already unsustainable, and the extent of the problem is going to increase without any radical changes. AC use leads to AC reliance through several different feedback mechanisms (Lundgren-Kownacki et al., 2018). The heat released by ACs contributes to the urban heat island effect, which makes cities hotter and need more air conditioning. At the global scale, high consumption rate of ACs leads to burning more fossil fuels, which in turn leads to global warming and the need for more AC use. Finally, AC use leads to the loss of heat acclimatization which leads to further dependency on ACs.

The increase in AC reliance as a worldwide phenomenon is attributed to the rise of urbanism (Rodrigueza & D'Alessandrob, 2019). Urbanism is linked to economic development and subsequent increased consumption from higher comfort standards, which includes thermal comfort and ACs. This will be further explored in chapter 4. Chang and Winter called this link between ACs and modernity 'thermal modernity'. They emphasised that analysing AC reliance needs to be part of a wider socioeconomic discussion about the change from traditional to modern lifestyles. They argue that:

To understand how technology shapes society through soft determinism, it is important to see technology as not a thing in isolation but as part of a complex system that is deeply embedded in society' (Chang & Winter, 2015, pg.95)

Up until the last studies in the early 2000s, people in Khartoum lived predominantly outdoors, as will be further elaborated on in chapter 2. Which means the transition to an indoor based lifestyle occurred in just 20 years. To put things into perspective, Nick Baker called the 15 generations (around 300 years) it took for this transition to occur in western countries 'a period of little consequence in evolutionary terms'(N. Baker, 2006). ACs provide an 'easy' fix, an alternative to passive solutions (Guedes & Editors, 2019). They can provide comfortable conditions, regardless of the local context at a high energy cost. They are an unsustainable short-term solution to change.

Heraclitus, a Greek philosopher, is quoted as saying "change is the only constant in life". Though change has always been constant, it has historically been slow, which allowed vernacular architecture to adapt to its occupants changing needs (Estaji, 2018). Through centuries of trial and error, it evolved using incremental adjustments to sustainably meet complex sociocultural needs within the constraints of local climate and available resources (Al-Azzawi, 2010; Mahmoud, 2016a; Mukhtar, 2020). It is still very relevant in Sudan given how recent the changes have been and the fact most rural areas still lack electricity, let alone ACs. This means that lessons can be learned from it and implemented in buildings designed for a modern internal-based lifestyle. This is the research gap targeted by this study. AC reliance in Sudan is a budding problem, which means that long term solutions applied now would have a large impact on kerbing further unsustainable development in the housing industry.

1.2. Research Aims and Objectives

The primary aim of this thesis is to address the problem of AC reliance in Sudan from a socio-technical perspective, developing a framework for the design of buildings that can sustain a modern lifestyle using reinterpreted vernacular principles of climatic adaptation. The goal is to find a way to modernise traditional architecture and adapt modern buildings to the local context, bridging the gap between the two. Both typologies are targeted as they are both contributors to the current energy crisis. A holistic approach is necessary to address the problem at different levels, which forms the basis of the three subsidiary aims needed:

Subsidiary aim 1: Understanding change in the wider context

Objective 1.1: Establishing the baseline before modernity impacted the local architecture.

Objective 1.2: Tracing how socioeconomic changes altered the Sudanese house

Objective 1.3: Identifying the current socioeconomic climate

This study aims to find inspiration from traditional architecture, which requires understanding how it originally functioned. This includes understanding the expectations and lifestyle of occupants in the past, as these were integral parts of how the architecture worked. This requires a socio-technical study that focuses on historical data. This study will then trace the evolution of both buildings and occupants as they adapt to the socioeconomic changes that started with the introduction of modernity. This highlights the importance of different design features and if they must be maintained to preserve the building's ability to function. It also provides insights on ways to adapt to change that can be used in modern buildings. Finally, it is empirical to understand the local socioeconomic context and how it is currently impacting buildings. This will identify the challenges the new typology needs to adapt to.

Subsidiary Aim 2: Understanding change at the building level

Objective 2.1: Tracing the evolution of sampled Traditional buildings

Objective 2.2: Tracing the evolution of sampled Modern buildings

As mentioned previously, change happened at the building level in addition to the wider socioeconomic and urban levels. The case study buildings in the 2018 study were not always AC-reliant; therefore, it is imperative to understand what changed. This means tracking the building's history and how the occupants changed during this time. This is similar to objective 1.2 but at the building level instead of the typology level. It is also important to understand why these changes happened and their implications. This needs to include traditional and modern buildings.

Subsidiary Aim 3: Understanding the current context at the building level

Objective 3.1: Defining how the occupants currently use the building

Objective 3.2: Gain in-depth insight into the building's thermal performance in light of the changes made to its building fabric and form.

This research aims to gain an in-depth understanding how both physical and behavioural adaptations affected building performance from the perspective of thermal comfort and energy use. Therefore, it is based on multiple-methodology research, involving interviews, environmental monitoring, studies of use behaviour and tracing the physical impacts of decisions made during the evolution of the houses. All of this is necessary to decide what needs to be changed to meet the occupants' new demands efficiently.

These three subsidiary aims are crucial to create a solution that addresses underlying issues of AC reliance from a socio-technical viewpoint. This does not mean striving to eliminate ACs, which is difficult in an extreme climate like Khartoum, especially given modern expectations. It instead means finding an energy-efficient way to integrate the AC into the building fabric and occupant lifestyle of both typologies. A methodology for facilitating 'sustainable development' in the context of housing design because the current way of adopting modernity is unsustainable. The study also does not aim to revive traditional architecture because, despite its efficiency, it came with health, safety, size and permanence concerns (Rapoport, 1969).

As a socio-technical study, its focus extends beyond the physical building to understanding the cultural change that manifests itself into new types of building typologies. It tracks the building and users' development by taking different snapshots of the ongoing change.

Efficient environmental solutions need to encompass more than just the building fabric and include how buildings are designed and used. For example, understanding occupant behaviour helps avoid the 'rebound effect' where improved conditions lead to improved comfort standards and then increased energy demands (Paone & Bacher, 2018). Research is needed to define the required social parameters that environmental solutions need to meet. This is especially critical in transitional contexts like urban areas in developing countries. These communities aspire to a modern lifestyle while holding on to their traditional values and the choice of how to achieve this balance will differ in each society. An example of this is privacy and segregation, this need might be so strong that different groups have to be physically separated by large distances (Muller, 1984a). Over time it may reduce to accepting adjacent but separate spaces like in institutional houses (K. M. Osman & Suliman, 1996) or shared spaces with a visual barrier like a curtain (Muller, 1984a).

Creating solutions that do not suit the socioeconomic context reduces their chances of being adopted by users or being used in the intended way. An example of this can be seen in Hassan Fathi's Gourna village. Though his mud houses in Egypt were affordable and had a small environmental impact (Mahmoud, 2016a), they did not consider that mud is strongly associated with poverty (Bertini, 2020) or take into account factors, such as limited durability of traditional materials or the need for vertical expansion (Mahmoud, 2016b). Fathi's buildings were replaced by airconditioned buildings, constructed in concrete, in order to meet these cultural expectations (Mahmoud, 2016b). Another issue was that these buildings were too 'pristine' which limited the occupants ability to shape them to reflect their individual tastes and needs, a social trait that was important to them (Mahmoud, 2016b). Their original village was made of 'low road' houses, buildings that do not hold a high value, allowing the occupants more freedom to customise them (Brand, 1994).

1.3.Research structure

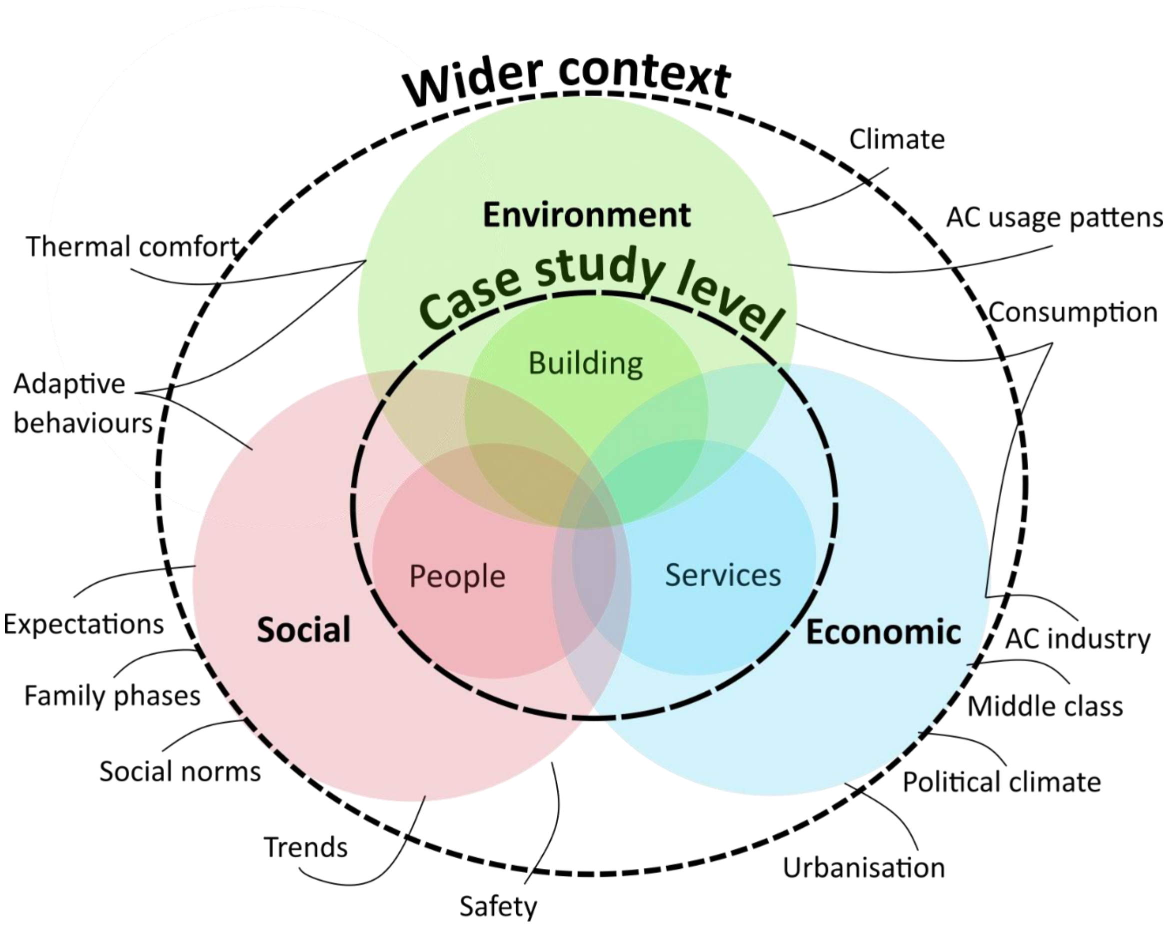


Figure 1.2 Research structure

This study focuses on understanding the wider context of change looking at social, environmental and economic factors, and to explore how these manifest themselves at the building scale through a series of case studies. These factors are important as they are the three pillars of sustainable development. The wide array of topics that will be covered in the wider context will be used to understand the case study level, which encompasses the building, people and services. The wider context will be covered first through literature reviews and interviews with experts in the industry. Chapters in this research are divided by topic, not methodology, which means that several methodologies are used in most chapters.

The second and third subsidiary aims set out in the previous section are concerned with the building scale, which is achieved using five case studies. The qualitative methods in the case studies include interviews, occupant logs, observations, building surveying and thermal imaging. This will be supported by building monitoring to record AC use, electricity use, space use, air temperatures and humidity.

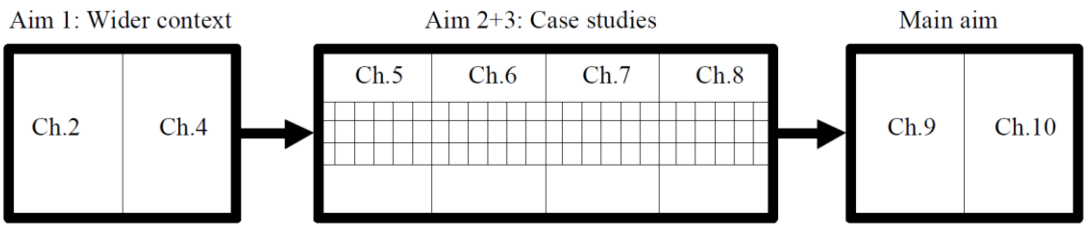


Figure 1.3 A graph showing the transition from the big picture to specific details and back to the big picture throughout the thesis and inside each results chapter

To capture important details without losing sight of their impact on the overall argument, the transition from 'big picture' to 'details' and back to 'big picture' will happen at both the thesis scale and the chapter scale (Figure 1.3). At the case study level, each chapter starts with an overview of the wider context before going into the details of the specific topic. Then the discussion and conclusions will take the reader back into the 'big picture' mode as the implications of the chapter are discussed.

1.4.Thesis structure

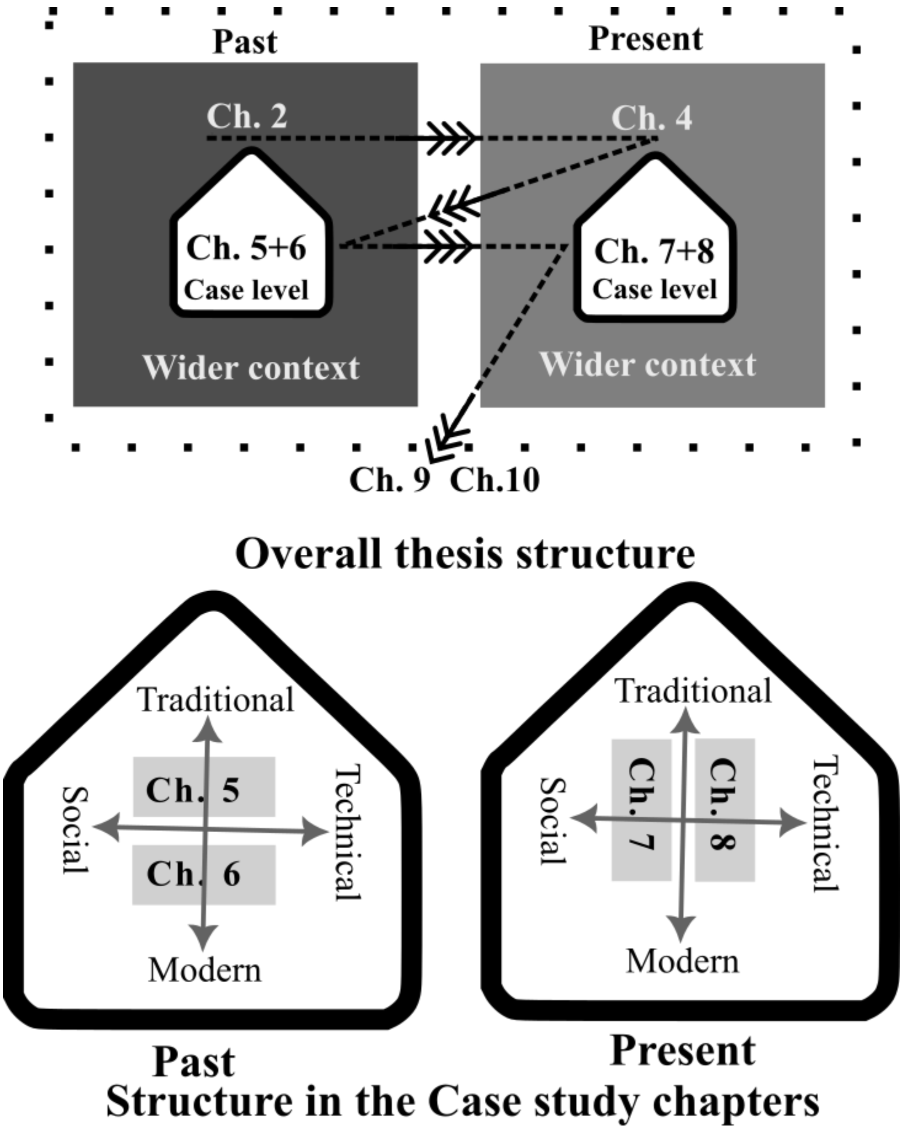


Figure 1.4 The thesis structure

Figure 1.4 reflects the journey through themes and contexts that the thesis will go through in the chapters. Chapter 2 is the starting point as it explores the historic wider context. After examining the lifestyle in the original rural house to set the reference, it will examine the socioeconomic factors that changed the Sudanese house. These factors will then be examined in the current wider context in chapter 4, which focuses on two aspects: urbanisation in Khartoum and the middle class and their consumption habits. These two chapters cover Aim 1: Understanding change in the wider context. Chapter 3 will discuss the methodology in detail.

Moving away from the bigger picture, the following four chapters about the research results will concentrate on the details of the case study buildings. Chapters 5 and 6 are about the building's past, while chapters 7 and 8 reflect the current conditions. The bottom half of Figure 1.4 shows the detailed themes within the results chapters. Chapter 5 and 6 were segregated based on typology as the historic change pattern is similar within the typologies. These two chapters begin with an overview of the neighbourhood of each case study. This is followed by a history of the family and house and the stages it went through. Finally, a discussion identifies the similarities and differences between the cases. These two chapters meet the objectives of Aim 2: Understanding change at the building level.

Chapters 7 and 8, focus on the current conditions in both typologies, looking at social and technical factors respectively. This is because occupants in both typologies lived a similar modern lifestyle. Chapter 7 will look at occupants current usage patterns, their AC consumption habits, and its implications for energy consumption. The chapter also highlights behavioural responses observed in the case studies as a coping mechanism to the extreme heat. Chapter 8 investigates the thermal conditions throughout the day, looking at the impact of building form, building fabric and air conditioners. Aim 3: Understanding the current context at the building level, is addressed through chapters 7 and 8.

The results will be reviewed critically in the discussion Chapter 9. This will be used to discuss the proposed solution framework and show how it meets the parameters set by the previous chapters. The chapter will proceed to apply the framework to two case study buildings, which is the main aim of this research. Finally, the Conclusions chapter will reiterate the key messages, identify the limitations and discuss future work. It will also reflect on the methodology used in this research and the resulting practical framework.

Chapter 2 The evolution of the Sudanese house

2.1. Introduction

This chapter explores how sociocultural forces initially shaped the Sudanese courtyard house. Comprehending this allows for new interpretations that can fulfil both traditional sociocultural needs and modern living requirements. This, in turn, allows for more successful solutions beyond superficially copying ideas without adaptation. The chapter will then explore the socioeconomic changes that happened and how they changed the building and its use patterns. The building stock in Khartoum is varied, and many of these mid-evolution stages still exist in the current building stock. Understanding the reasoning behind their design will help decide which elements must be preserved and which can be altered when retrofitting for improved environmental performance.

Rapoport details the relationship between house and form from an anthropological perspective in his ground-breaking book ‘House, Form, and Culture’ (Rapoport, 1969). He stated that sociocultural forces are the key determinant that shape a house’s form. However, the surrounding climate adds additional environmental requirements and the technology available determines the tools needed to create this form. That’s why he called the climate and technology ‘modifying factors’. His theory helped explain why people build different types of houses within the same climate type and available materials. Sometimes the sociocultural aspect is so strong that it leads to forms that do not suit the surrounding environment.

In Africa, sociocultural and environmental factors are still the most significant determinant of house forms (Jiboye & Ogunshakin, 2010). Yet anthropological studies in Africa often neglect the relationship between spatial aspects and social relationships (Muller, 1984a). One of the few studies that highlighted this interaction in the Sudanese context was Mahgoub’s study on the nomadic tents of the Rashidaa and Hadendawa tribes in Eastern Sudan (H. K. Mahgoub, 1988). Though this study focuses on permanent houses, the tents provide a rich example of the cultural diversity in Sudan and its impact on form.

Both tribes lived in the same environment and had access to the same materials, but their different cultures resulted in two different tent types. The Rashidaa immigrated from the Arab peninsula 200 years prior and brought with them the open Arab tent that suited their hospitality-based culture. Thus, the tents were always open, welcoming visitors, as shown in Figure 2.1.

Figure 2.1 The Rashaidaa open tent. Source: (Mahgoub, 1988)

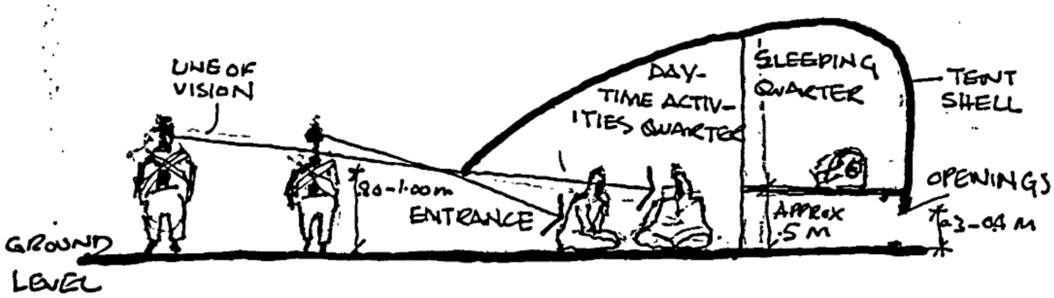


Figure 2.2 The Hadendawa tent with complete privacy from the outdoors. Source: (Mahgoub, 1988)

The Hadendawa tribe are very conservative, and their tents reflected that with the closed cross-section that allows complete privacy, as shown in Figure 2.2. The tents were arranged to look like hills to camouflage themselves, unlike the Rashidaa tents, which were bold and easy to spot with their dark colours and spikey points. Finally, even the placement of the tents differed; the Rashidaa placed the tents close together, while the Hadendawa left a large distance between tents (H. K. Mahgoub, 1988).

Sudan has a variety of vernacular house types depending on the area. This chapter examines the courtyard house as it slowly changed into the contemporary house. Houses in Central Sudan have had to adapt and change as socioeconomic conditions shifted in the past 200 years. The primary resources used in this chapter are two studies from the 1970s that documented life in rural and urban courtyard houses (Ahmed, 1978; Elias, 1970b) and two studies of courtyard houses that existed in the late 1990s (Merghani & Hall, 2001; K. M. Osman & Suliman, 1996). Osman focused on surveying house types in Omdurman (Osman & Suliman, 1996). Her study looked at the houses in their current form and briefly mentioned the common construction periods for each typology as shown in Figure 2.3. This study went on to take this information and reconfigured it chronologically. This meant increasing the focus on the era at which each typology first emerged and the surrounding socioeconomic context that shaped it.

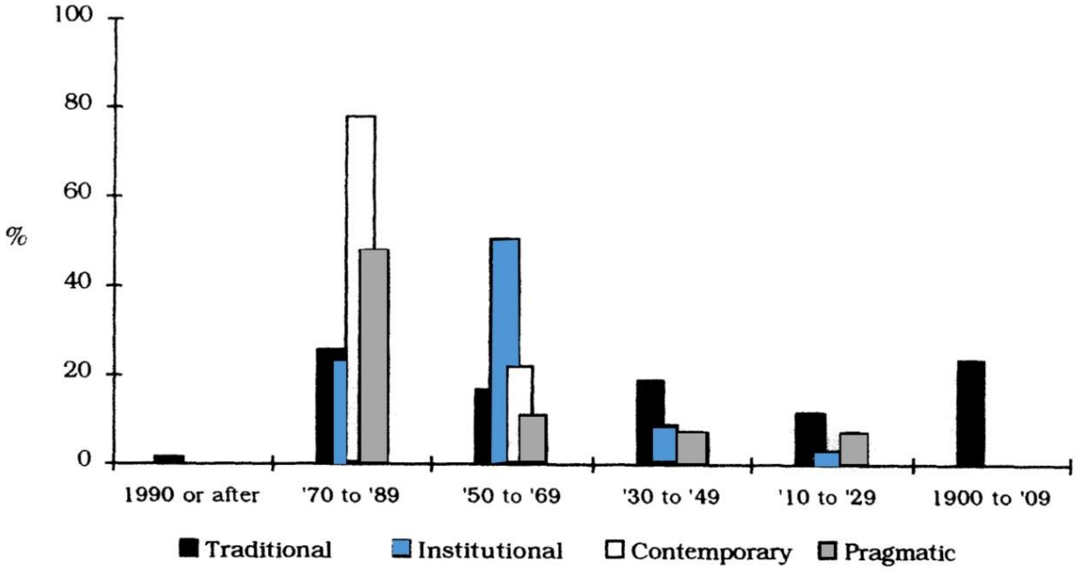


Figure 2.3 Percentage of each typology built in different eras. Source: (Osman & Suliman, 1996)

Osman's study divided the houses into Traditional, Institutional, Pragmatic and Contemporary, which will be explored in this chapter in that order. The rural house was not included in Osman's study as she focused on the urban context of Omdurman city. However, most other studies name the different variations of the courtyard house in Sudan under the umbrella term' traditional house' or 'courtyard house' (Ahmed, 1978; Elias, 1970b; Madibo, 1989; Merghani & Hall, 2001; A. Osman, 2014).

2.2. The features of Sudanese society that shaped the rural house

Amos Rapoport states that the key social features that impact built form are privacy, the position of women, social intercourse, family and basic needs (Rapoport, 1969). This section, which is based on a literature review, will explore these critical components in Sudanese society and how they impacted the building form in the rural house in Central and North Sudan. These features will also be contextualised within the scope of Africa and the Middle east due to the dual identity of the Sudanese people. This will serve as a starting point to understand how a change in these features has led to the changes in Modern homes.

Privacy and segregation

Islam is the dominant religion in Sudan and has impacted people's lives in many aspects. Women are considered sacred, which is why their privacy is of the utmost importance (Mohammed & Kurosawa, 2005). Islamic architecture often used courtyards to provide privacy and seclusion. Archaeological evidence suggests that courtyards did not exist in the Christian and Pre-Christian eras in Sudan; they were a cultural by-product of the Arab migration to Nubia in North Sudan. (A. Osman, 2014). To preserve privacy, men and women are segregated when unrelated. Fawzi best describes this: *"Seclusion of women, certainly, does not mean the division of the members of the same household into males and females, who, though residing together, have virtually separate lives … 'seclusion' is valid only for one sex in relation to the 'stranger' or 'outsider' of the opposite sex"* (Fawzi, 1954, p. 102).

This means female guests must be segregated from male residents, and male guests must be separated from female residents. Gender stereotypes are strong, with women's activities mainly occurring within the household, such as cleaning and caring for livestock. Men's activities focused on the outdoors, such as going to the market and working (Osman & Suliman, 1996). This created two zones in the Sudanese house, an outer public male zone and an inner private female zone (A. Osman, 2014; K. M. Osman & Suliman, 1996). Maintaining women's privacy inside the house influenced the architectural design in several ways.

For example, the outer yard walls should be high, the gate should not face female zone's windows, and house doors do not directly oppose each other (Elias, 1970b). Women's activities are considered less formal than men's (A. Osman, 2014). This is why visitors are entertained in the guest room, 'Diwan' or 'Saloon' (Male spaces) if they are outsiders, and in the family room, living room, hall or female veranda (Female spaces) if they are kin.

Though Sudanese people are private, this did not lead to an introverted design such as the central courtyard building found in the Gulf region(Remali et al., 2016), Iran(Foruzanmehr, 2018), Turkey(Eyüce, 2012) and Egypt(Abdelsalam, 2017). The Sudanese courtyard house has closer resemble to the African courtyards like the Nigerian Hausa, as seen in Figure 2.4. These buildings are more adeptly called compounds in the African (Ikudayisi & Odeyale, 2021; Muller, 1984a) and Sudanese context (Elias, 1970a; A. Osman, 2014).

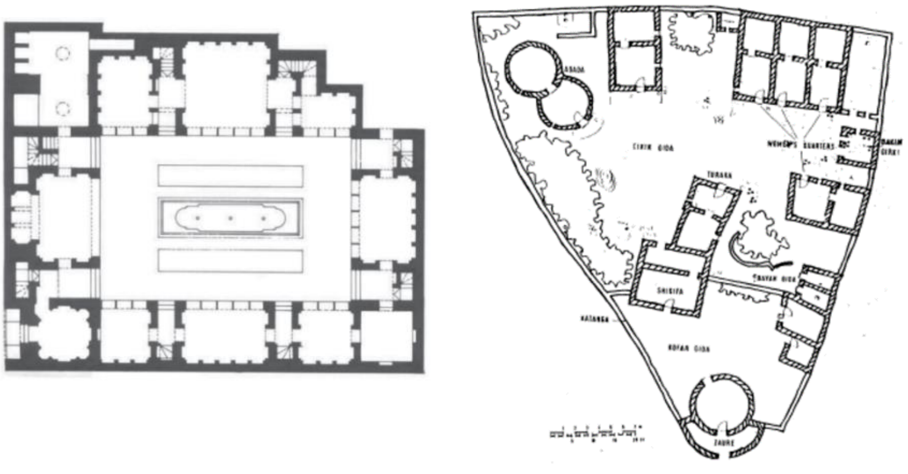


Figure 2.4 (Left) A plan of an Iranian courtyard house. (Right) A plan of a Hausa compound in Nigeria

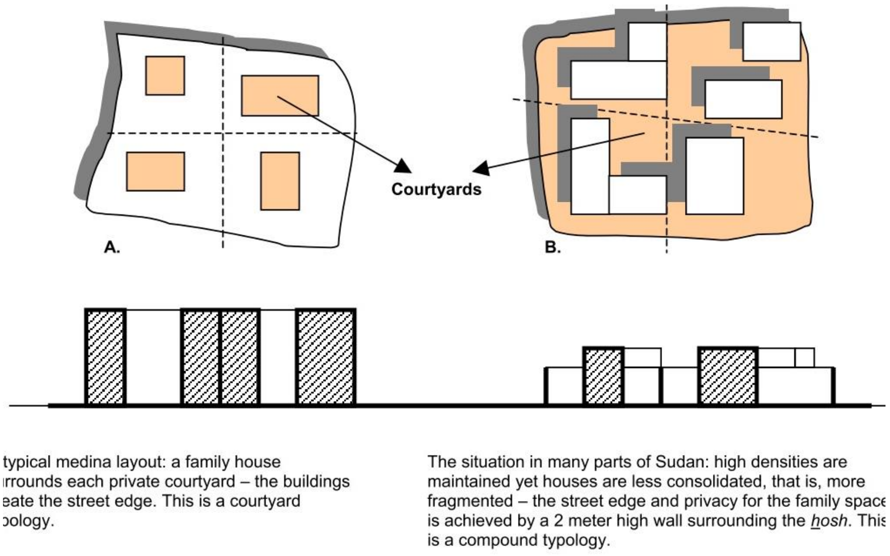


Figure 2.5 A comparison between the Medina and Sudanese Housh-style towns. Source:(A. Osman, 2014)

This difference between courtyards and compounds also extends to the typology of the towns and villages as a whole, as illustrated by

Figure 2.5. It should be noted that in hot climates, internal, external and boundary walls are usually of similar thickness. Which is why boundary walls are visually distinguished in plans using halftones The openness provided by the compound typology allowed for the Sudanese household to extend organically into the outdoors, as seen in Figure 2.6.

This means that instead of the typical stark contrast between the public street and private home, the space sequence extends from the private rooms to semi-private shared spaces to courtyards and the street, finally ending at the public open space. This spatial connection and gradation from private to public is common in Muslim countries (Eyüce, 2012). Streets enabled male socialisation and children playing, while open spaces accommodated social events like weddings, especially in tight urban plots (Ahmed, 1978). The upper image in Figure 2.6 shows these different events, while the lower one shows an illustration of one of those events: a Ramadan meal on the street floor.

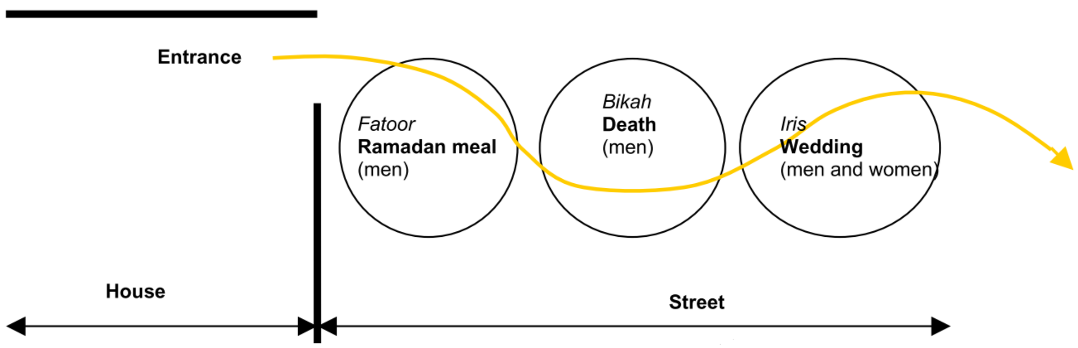


Figure 2.6 Top: The street as part of the Sudanese home. Source: (A. Osman,2014) Right: An artist illustration depicting the males eating together in the street with neighbours in Ramadan. Artist Abu Alhassan Madani in 2007.

Socialisation and individuality

Sudanese families are 'society orientated' with strong feelings of community among the residents of each neighbourhood. Architects who failed to recognise this aspect created designs that were rejected by the local community because they imposed unfamiliar structures of activities and functions (Ahmed, 1978). Nuclear family households are households that only include parents with their children. When additional members, such as grandparents, also live in the house, it becomes an extended household. African families traditionally lived in extended family structures, which helped pool resources to smooth economic depressions. This was crucial to survive the lack of insurance, government social support and credit systems (Orazem et al., 1999). The amount of support available varies depending on the relationship level. Nuclear families have the strongest ties and are more motivated to commit more resources than extended family members (Hamid & Elhassan, 2014). This is further reduced if the extended family lives in separate houses.

Islam encourages maintaining kinship ties and good relationships with neighbours. All Muslims are considered brothers, and wealthier members are responsible for the welfare of their poorer counterparts, especially if they are related (Ahmed, 1978). Widowed mothers are absorbed into another family with their children because they usually cannot support themselves independently (Ahmed, 1978). Another impact of this support is that families frequently take in lodgers, especially urban families with rural relatives(Elias, 1970b)(Fawzi, 1954)(Ahmed, 1978). This is because most jobs and higher educational opportunities are in these urban centres, and strong social ties create a preference to stay with family rather than renting or living in a dormitory. Lodgers live with the family during the day, with females helping with the household tasks and males eating with the male house head. However, sleeping arrangements are separated, especially if the lodger is an entire family.

The extended family setting has many benefits. Larger households are more efficient and produce less waste than smaller ones (Klocker & Gibson, 2013). Compared to one-person households in the US, two-person households spend 17% less energy per person and three-person households 33.3% less energy per person (Chen, 2002).This is because they share energy (trips to shopping), space (garden space) and resources (leftovers, furniture) (Klocker & Gibson, 2013). There are also social benefits. The 'Haboba' or Grandmother in Sudanese households transfers her cultural identity to her grandkids and teaches them how to conform to societal standards. Habobas also provide social and logistical support to mothers and their young children (Alawad & Sonnga-Barke, 1992).

'The individual family is 'society oriented'; the man spends most of his day out of the home mixing with other men of the household or tribe, and the wife finds her companions among other women. Wife and husband rarely mix together or eat together during the day because they consider themselves part of a big household or a big society towards which they have certain obligations and certain roles to play.' (Elias, 1970b, p. 32)

The priority is to the community over the individual. Female and male zones are accessible to the community at all times, with guests coming without announcement (A. Osman, 2014). Silence, solitude, individuality and privacy are considered unnatural and unhealthy (A. Osman, 2014). *'The creation of private space, free from intrusion and public interest, is viewed with suspicion.'* (A. Osman, 2014, p. 98). Everything is shared; people sleep in whatever bed is available that night in their zone rather than have a bed in their name. Part of being 'society oriented' meant that socialising was part of household chores such as cooking, making tea and preparing the yard for sleeping (K. M. Osman & Suliman, 1996). In a 1970 low-cost housing scheme, spaces were not adequately planned to cater to the leisure aspect of housework, which led to inefficiently utilised spaces (Elias, 1970b).

Maintaining social status is vital in Sudanese society. Social status dictates that the family stays in one room and devotes the other room to guests when only two rooms are available (Elias, 1970b), which is the usual case. This causes overcrowding as the guest reception or guest room is usually the biggest room and costs a third of the house's total cost due to improved construction and furnishing. However, it is only used for 5-10 hours once or twice a week as guests are received more frequently in the family area. The guest room is also better maintained compared to the remaining house areas. 55% of residents in the previously mentioned 1970s housing scheme were unsatisfied with the size of the family room because they left the other room for guests. The lack of a store room in the scheme meant these rooms were also used for storage, which further exacerbated the overcrowding. (Elias, 1970b)

The lifecycle of a Sudanese family

Elias highlighted the importance of planning for a family's growth when designing a house for several reasons (Elias, 1970b). He emphasised that the growth leads to relationship restructuring which impacts space use patterns. People also change their lifestyle as their economic status changes, which includes furniture and appliances, which leads to changes in space needs. A house that cannot adapt to change becomes obsolete (Estaji, 2018). Elias summarised the Sudanese family lifecycle into 4 phases (Elias, 1970b) shown in Figure 2.7.

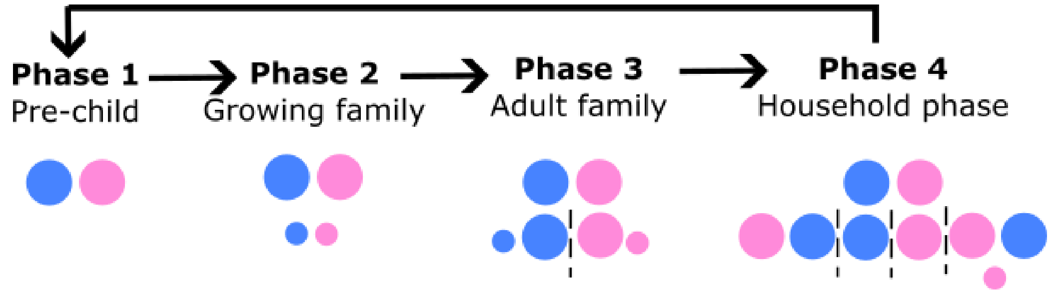


Figure 2.7 The lifecycle of a Sudanese family. Illustrated by: Author

The first phase is the Pre-child phase, which starts with the married couple and ends a year or two after their first child. In Sudanese tradition, married couples stay with their parents for the first year (Fawzi, 1954). If the couple is from a lower economic status, this phase can extend to several years until the family can afford to move out. In some cases, they never move out. The family usually has their own room and veranda for privacy but share facilities like the kitchen and bathrooms. Some families separate sections of the house to act as independent yet linked units.

The second phase is the growing family phase, where the increasing number of children creates a need for separate living accommodations. The most important family need during this time is sufficient plot space. This is because the family can barely buy land during this time and usually does not have the means to build an entire house. Very few can buy in the private market or afford governmental housing. They can start with a small space and gradually increase rooms and services and upgrade building materials so long as they have the land space to grow. Families from this phase constitute the bulk of the housing needs. Most rural immigrants moving to the city are in this family phase.

The Adult family phase is distinct because adult children in a Sudanese setting require increased privacy and segregation between male and female children, as shown in Figure 2.7. This translates into the need for more rooms and courtyards, or else overcrowding and lack of privacy become problematic. During this phase, the family's income is at its best because the household head has not retired yet. Additionally, some of the children are employed and helping with the expenditure, and most large expenses, such as mortgages, are finished. The family invests in improved living conditions, such as adding verandas, installing tiles on the floor, and better wall finishes and furniture for living rooms. All these changes are aimed at exhibiting the social and economic status of the family. Their established state allows them to create strong ties with their neighbours as they will not likely move.

The household phase is the last, as the marriage of children does not result in an empty nest as it would in a European family. Opposing forces keep the family size relatively stable. On one side, the family during this phase can take in lodgers or married children who may stay temporarily or permanently. On the other, some children move out if there is not enough space or their job is far away or abroad. During this stage, it is essential to keep privacy between the sexes and between different families, as shown in Figure 2.7. Families in their first and last stages are more likely to be multifamily households (Elias, 1970b). This is because they are either a small young family that can be absorbed into a larger household or an established family with married children that they can sustain. Families in the middle stages have higher spatial needs, which is why they are usually in their own house. (Elias, 1970b).

Migratory behaviour

The fact that Sudanese families do not assign rooms to individuals or tasks helps them use these spaces more flexibly for different activities. Because of this, built areas are called 'rooms' and not assigned specific titles like 'living room' or 'bedroom' (Elias, 1970b). Osman (1996) stated:

'The distribution, as well as the spatial arrangement of spaces in the houses of Omdurman, does not express a clear distinction between diurnal and nocturnal activities; at the same time, they do not specify spaces for private or collective use as observed in western houses. Any activity can take place in various parts of the house depending on the character of the activity and the status of its participant … by the same token, many different activities take place in the same place' (K. M. Osman & Suliman, 1996, p. 418)

Sudanese homes have a wide variety of spaces available, which is why moving between spaces is a commonly used behavioural adaptation (Merghani, 2004). There are indoor built spaces like rooms, semi-outdoor shaded areas like verandas and under trees and open spaces like the courtyard. The space variety supports different thermal zones, enabling occupants to choose where to perform their tasks based on the most comfortable zone.

Ahmed conducted a detailed study on how occupants used the outdoor space in a courtyard house throughout the day and mapped the results on Figure 2.8 (Ahmed,1978). It echoes the patterns shown by the other anthropological studies conducted before 2001, with the added benefit of showing the monitored temperatures in a summer day as these transitions occurred.

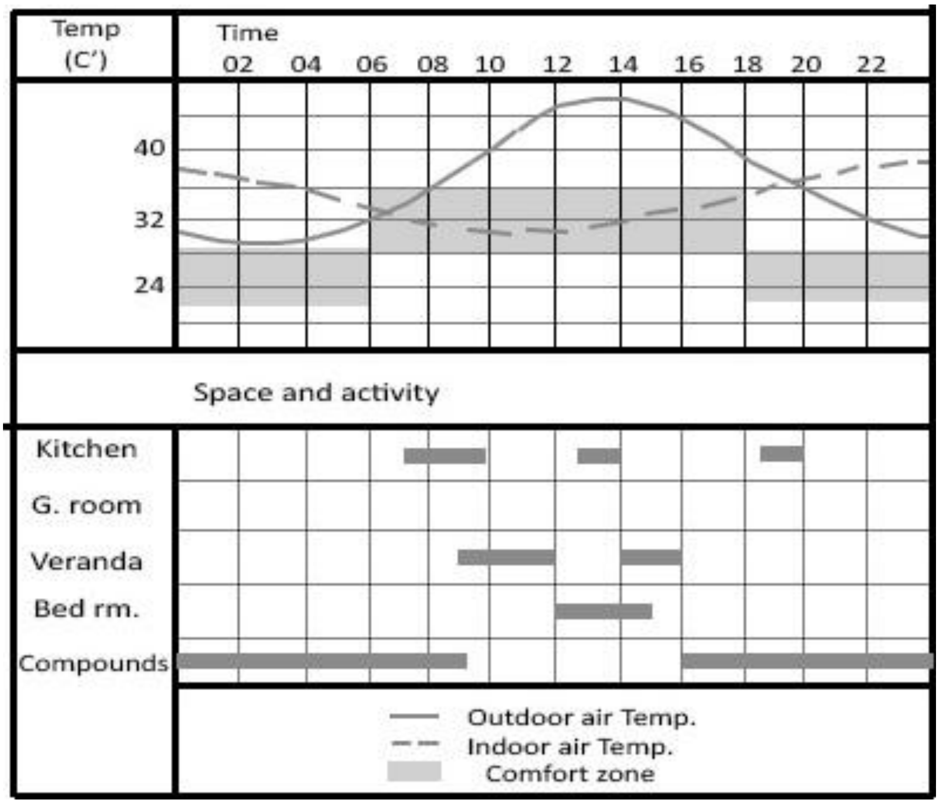


Figure 2.8 Space use and daily temperatures in a traditional setting. Source: (Ahmed,1978)

Figure 2.8 shows that indoor spaces were hotter than the outdoors from 8:00 pm to 6:00 am, which is why people spend that time sleeping in the courtyard. The inner courtyard is used intensively for social activities such as eating, sleeping, and playing and for services such as cooking and washing dishes and clothes. Most social activities occur after 5 pm, when it is cool. Children sleep with their parents in the yard in the family zone, and adult sons sleep in the guest zone. Despite some families having a 'master' bedroom, the parents rarely slept in it. Female adults are also separate but sleep in the family yard. The male yard is mainly used for guests, as the men usually spend their time with their families in the inner courtyard. They would also occasionally sit in front of their homes to drink tea and chat with neighbours and passers-by. Despite being less used, the male outer yard was usually bigger than the inner family yard (Elias, 1970b). Extensions are also usually made towards the inner courtyard, which causes overcrowding (Elias, 1970b). A subtractive growth pattern, where the external outline is fixed, and internal division is used to create more spaces, is common in traditional houses worldwide (Rapoport, 1969).

Rooms were sparingly used, especially if attached to a veranda. They were mainly used to store furniture and during extreme and winter weather conditions (Ahmed, 1978). This is because they were hot, dark and poorly ventilated during mornings, evenings, and nights (Elias, 1970b). Figure 2.8 shows that rooms were most comfortable between 12:00-2:00 pm when people take their siestas indoors. This shows that the migrational behaviour extends even to different seasons. Merghani observed that people in traditional houses spent 95% of their time indoors in winter but only 40% of the time in summer. He theorised that this is because the time lag, caused by the thick brick that most houses are made of, makes them uncomfortably hot during evenings. The family veranda was the most used space, especially during midday when it is too hot indoors and in the open yard (Ahmed, 1978). The men's veranda was only used to entertain guests and was usually tidier. Even though food was always stored in the kitchen, cooking happened in several locations. Usually in the veranda on a hot day or the living room during winter and in the open space during cool evenings and mornings. This is because most women wanted to socialise while cooking, which would be difficult in the confinement of the kitchen (Elias, 1970b). This shows that both climatic and social drivers drive migratory behaviour. Table 2.1 summarises these activities and where they typically happen in a traditional Sudanese household. It clearly shows how outdoor spaces are used more than indoor ones.

Table 2.1 Summary of the activities and where they happen in a Sudanese home. By: Author

	Indoor spaces			**Outdoor spaces**		
Activity	**Kitchen**	**Room**	**Saloon /Guestroom**	**Shed/veranda**	**Inner courtyard**	**Guest courtyard/ veranda**
Eating	Winter	Winter	Winter	Summer	Summer	-
Cooking	Usually	Winter	-	Weekends / hot days	Weekends/ evenings/ mornings	-
Entertaining guests	-	-	Strangers	Relatives in Evenings	Relatives in Evenings	Strangers in Evenings
Sleeping	-	siesta at noon	-	-	Parents + kids/ night	Male guests + adult males/ night
Chores	-	-	-	Before and after noon	Yes	-
Playing	-	-	-	Yes	Yes	-
Storage	-	Yes	-	-	-	-

The Rural Sudanese house

Figure 2.9 Artist illustrations showing a typical rural house. Source: Artist Osman AwadAllah in 2012. (Upper): The different chores done around the yard under the shade. (Lower) The family spending time in the evening socialising in the yard

Sudan was mainly composed of agricultural villages before the 19th century, with only a few towns selling agricultural goods. Many rural houses today remain as they were in that era. In rural families, most households are multifamily and are usually all related. Figure 2.9, which are paintings by the Sudanese artist Osman Awadallah, show a typical rural house yard. Most activities happen under the shade of the straw porch or wherever the shade is during that time of day (A. Osman, 2014).

'In traditional agricultural societies, the day starts early due to the extreme heat. The men would leave the house after morning prayers at sunrise. They would return at noon for a siesta and lunch and leave again for their work after the sun cools in the late afternoon. After-sunset prayers is the time for socialising. The courtyards are prepared: swept, sprayed with water, and the 'angaribs (traditional wooden beds -shown in Figure 2.9) brought out, and people find relief in the coolness after the harshness of the day.' (A. Osman, 2014, p. 97)

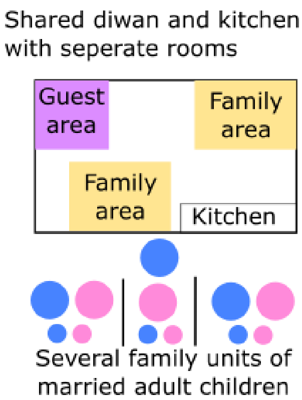


Figure 2.10 Author's interpretation of the zoning within the rural house

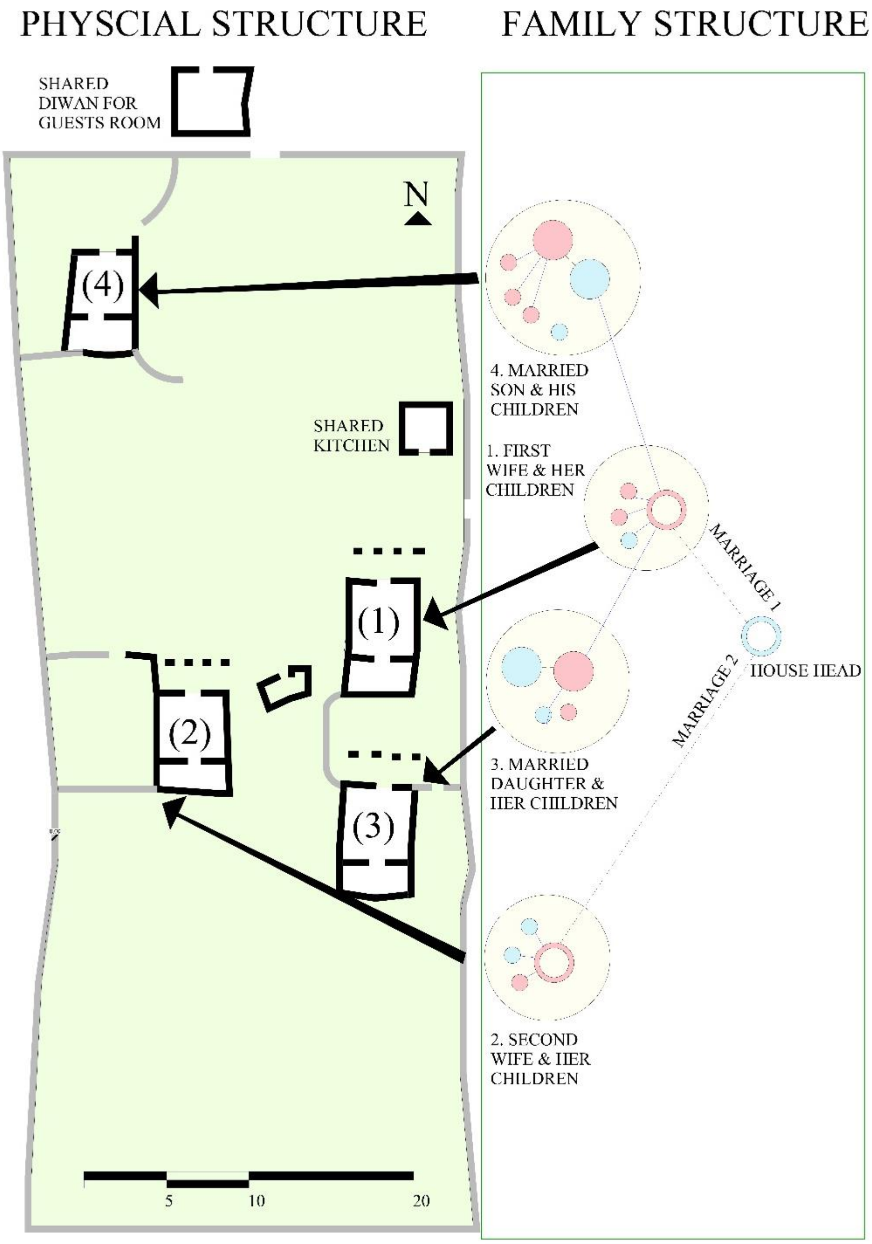


Figure 2.11 The family structure of a rural house and its physical structure. Though Elias (1970's) called it the 'Traditional house', it has been changed here to rural house to distinguish it from Osman's (1996's) Urban 'Traditional house'

Figure 2.11 shows how this family structure impacted the housing layout in a rural house (Elias, 1970b). The expansive space in rural areas sustained an organic expansion pattern. Each family had their own private zone to sleep in, but they spent the day together around the shared kitchen.

In suburban areas, ties are weaker than in rural ones but still stronger than in cities. This results in more clearly defined family units that are connected rather than one large single unit. The Diwan is a multi-functional space, as most spaces in traditional Sudanese houses are. It is a communal dining room where all the male household heads eat together and a guest room for those who sleep over. It is also used as a meeting room to discuss family affairs. Diwans in rural and suburban areas are shared between family units to receive large numbers of guests or events.

Figure 2.11 shows how the zones were divided into guest and family areas. People share the cost of an open tent during weddings and funerals to hold the event. Rural families are more 'society orientated' than urban families that are 'home oriented' (Elias, 1970b). This means urban homes have more privacy and more time is spent within the nuclear family rather than members spending most of their time with the extended family. A similar observation was seen in Nagpur, India (Kotharkar & Deshpande, 2012). Kotharkar compared three traditional houses in a rural, semi-urban and urban setting and noted that the house changed as occupants became more privatised, which reflected on the house form and space use patterns. People abandoned the open, flexible spaces for more enclosed private spaces with defined functions.

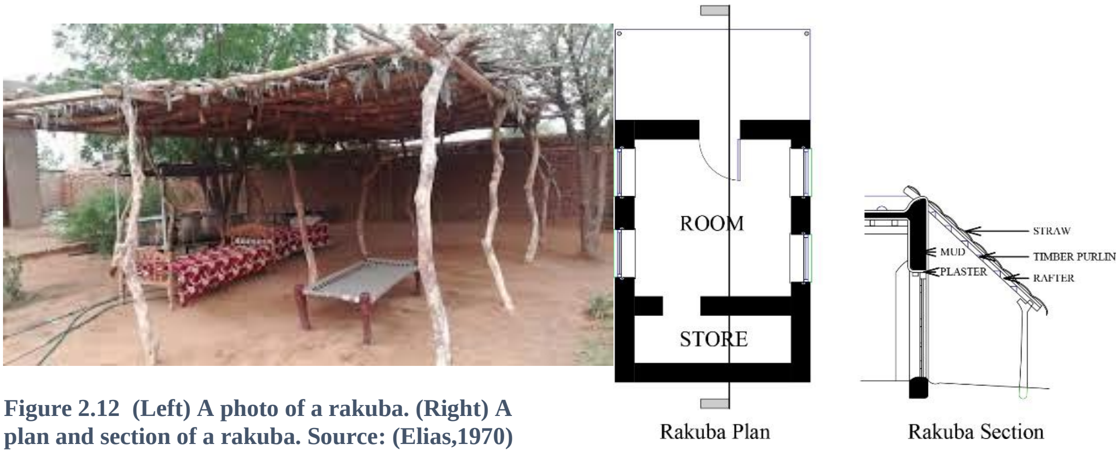


Figure 2.12 (Left) A photo of a rakuba. (Right) A plan and section of a rakuba. Source: (Elias,1970)

In Sudan, this can also be seen in the transition from the ‘rakuba’ to the ‘veranda’ to the ‘sala’, which marks the slow transition from open outdoor life into more private indoor-based lifestyles. The ‘rakuba' (Figure 2.12) in the rural setting was a straw structure open to society, simply a frame with a roof. Family members sitting in them would freely communicate with neighbours (Elias, 1970b).

In the urban setting, boundary walls prohibited this, and rooms were considered dark and poorly ventilated; therefore, the veranda (Figure 2.13) served as an alternative to the rakuba and functioned as the main living space. The veranda usually has a lightweight roof, such as timber boards or corrugated iron.

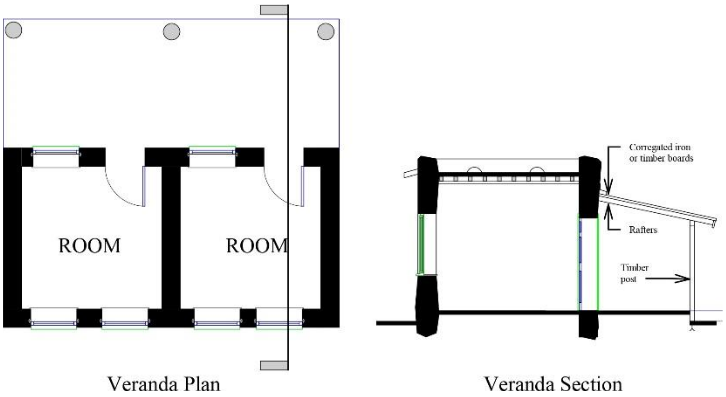


Figure 2.13 Plan and section of a veranda Source: (Elias, 1970)

Finally, the veranda was replaced by the sala or hall (Figure 2.14). The sala was an extension of the room and had a similar structure, making it more closed than open.

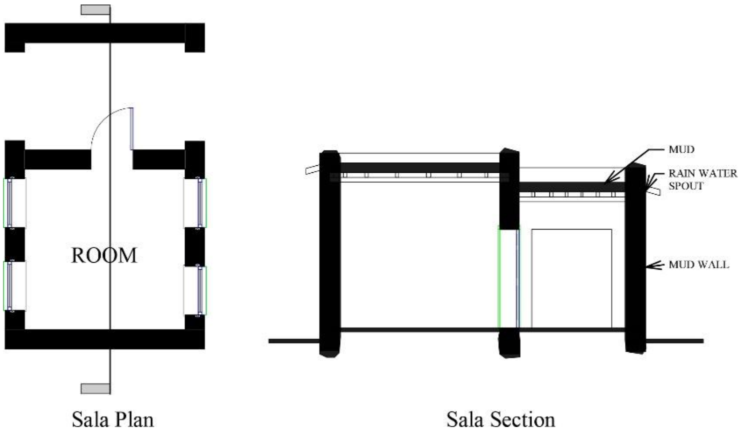


Figure 2.14 Plan and section of a Sala. Source: (Elias,1970)

The large north and south openings allowed the breeze to pass through and protect from the sun during mornings.

2.3. Colonialisation and the birth of the Traditional house

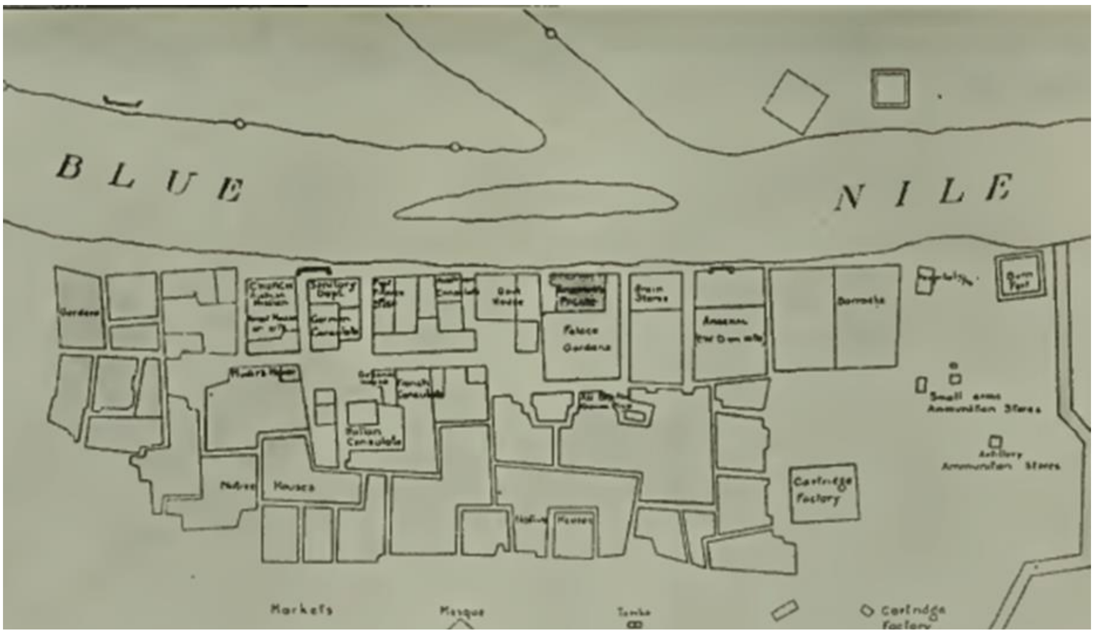


Figure 2.15 Turkish Khartoum in 1898. (Mclean, 1910)

As this thesis focuses on Khartoum, it is crucial to gain an understanding of the development of the city, with a particular focus on the origins of the urban house typologies. From 1820-1885, Sudan was under Turkish-Egyptian rule. It was the first form of a central government, as the land before was divided between small tribes. The Turks established their modern capital Khartoum in 1821. During the Turkish rule, Khartoum was a small town with irregular construction and narrow streets shown in Figure 2.15 (Petherick, 1846). Its population in 1850 was 30,000, living in 3,000 houses. The streets were impassable during rainfall (Melly, 1851). In 1862, Sir Samuel Baker described Khartoum as a filthy miserable and unhealthy spot. The houses were of unburnt brick (S. S. W. Baker, 1867).

When he returned in 1870, half the population had died due to a lack of sanitation and overcrowding. In 1880, Felkin says the sanitary arrangements were much better but being on a low land remained a problem (Walkley, 1935). Grand government buildings were nearly finished, and many good houses and a large hospital were being built. The Turks treated the Sudanese brutally, enslaved them and heavily taxed them (Martin, 1921, p. 17). These policies ultimately led to the Sudanese revolting in 1885 and, in the process, burning the colonial city to the ground. They built their own capital, Omdurman, using Khartoum's rubble directly to the west of it. Omdurman was built in the traditional medina style (see Figure 2.19), which suited the natives' environmental, cultural and social needs.

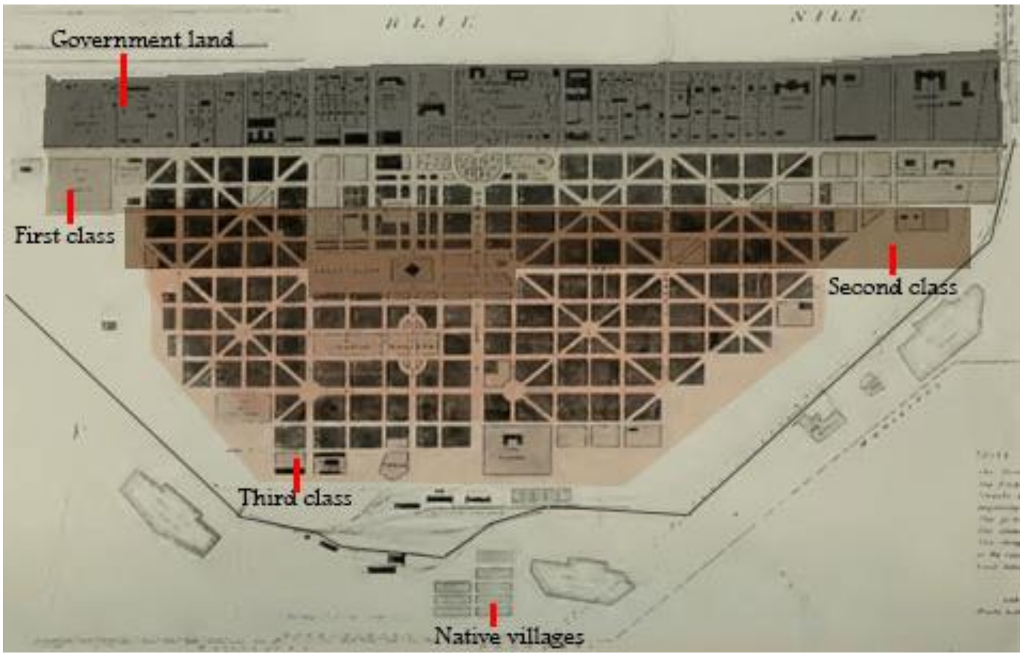


Figure 2.16 Khartoum and the three classes in 1908, Edited by author. Source: (Mclean, 1910)

Lord Kitchener reconquered Khartoum in 1898, establishing Anglo-Egyptian rule. The ambitious Kitchener started rebuilding Khartoum shortly after with the vision of creating an African utopia for Europeans. It became the central administrative town (Sarzin & Mehta, 2011). He divided the city into three zones, the prime Nile lands for Europeans, followed by the second class for Egyptians and the farthest third class for the natives. The first and second class were built in a European style with wide straight roads, regular plot shapes and brick facades. Mclean, the city's principal architect, had to find a way to adapt this European architecture to a hot climate. Drawing on the British experience in India and the American experience in the Philippines, he believed that extensive shading and high ventilation rates were vital to keeping white men healthy in Khartoum (Mclean, 1913, p. 225). Mclean's designs were characterised by double roofs, light colours and thick brick walls. Moreover, it involved the shading of windows and doors through verandas, louvres and trees and large yards were provided for increased ventilation and mosquito-netted cages on roofs for sleeping (Mclean & Hunt, 1908).

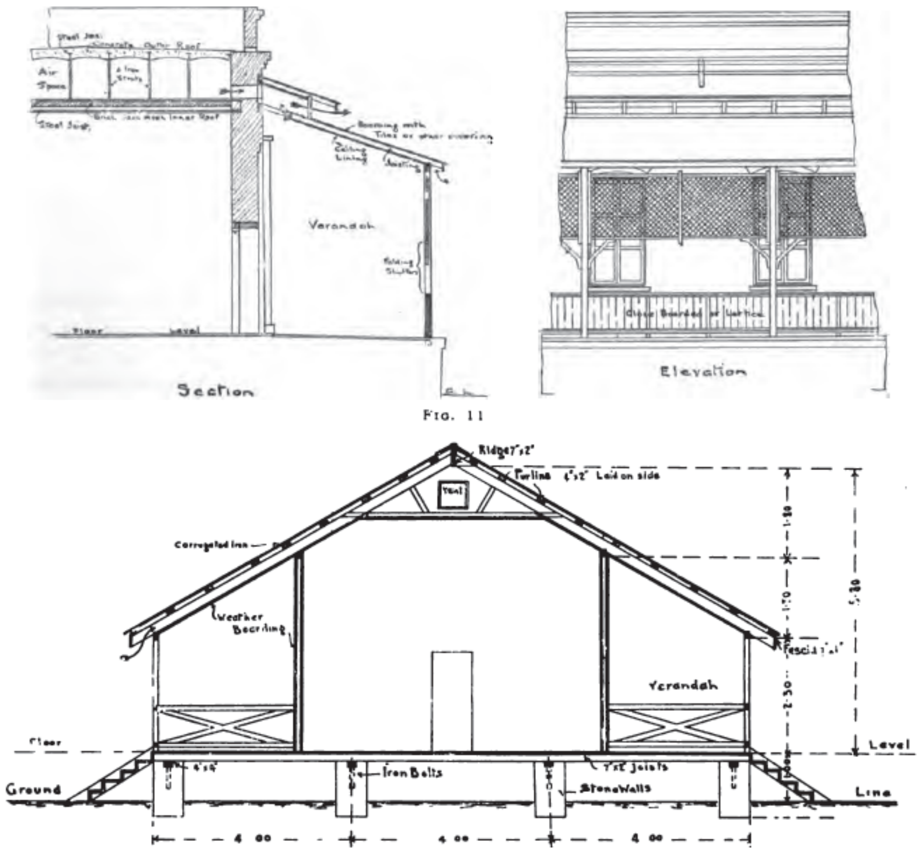


Figure 2.17 A pilot designed by Mclean showing an arid design (top) and a design for rainy areas (bottom). Source: (Mclean & Hunt, 1908)

Two of Mclean’s housing models are shown in Figure 2.17, a flat roof design for the arid parts of Sudan and a pitched roof design for, what is currently, the tropical areas of South Sudan (Mclean & Hunt, 1908). Despite the pilots reflecting McLean's awareness of the difference between hot-humid and hot-dry climates, the increased focus on ventilation was based on his cultural belief of its necessity for white men. Hot-dry climates actually need limited ventilation rates during the day. Another key issue is that Europeans lived an indoor-based lifestyle, while the natives lived an outdoor one. It could be argued that Mclean chose to adapt European architecture to the Sudanese climate rather than adopt the local architecture to maintain the modern lifestyle.

These colonial buildings (Figure 2.18) are the first attempt to sustain an indoor-based lifestyle without mechanical cooling in Sudan. ACs were invented in 1906 in the US (Sivak, 2009) but only reached Sudan decades later in the 1960s. However, the concept of internal living was not adopted by the natives until much later, after independence. Thus, for decades, these colonial buildings coexisted with the native ones in the same climate, with culture being the main reason they were different.

'One reason why westerners have been unable to use such court dwellings is the scale and arrangement of spaces, which are culturally unsuitable. Natives, on the other hand, have had to brick up openings in European houses, not only to avoid light and sun but also for privacy.' (Madibo, 1989, p. 23)

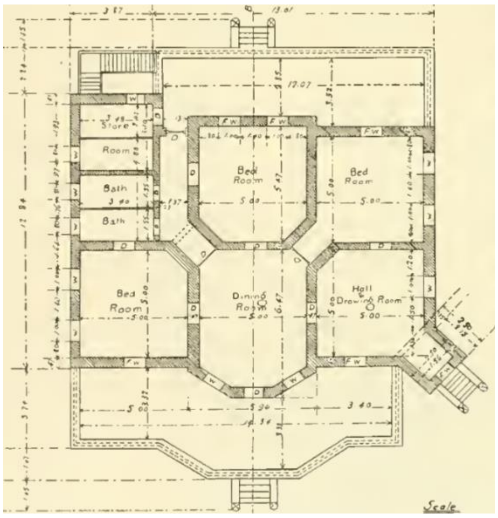


Figure 2.18 The plan of the pilot colonial house by Mclean. Source: (Mclean, 1910)

Interestingly, the contribution of colonisation in AC reliance in Sudan is limited to introducing the colonial house and cities, which can be perceived as an indirect effect. However, in Singapore for example, it lead to AC reliance due to the post nation building effort focusing on the association between ACs and progression, making it a much direct impact. This is why AC reliance in Singapore started as early as the 1930s (Chang & Winter, 2015) compared to the 2000s in Sudan. A theory that could explain this difference is the reason each country was colonised, which impacted the level of development they underwent. Singapore was an important trading centre, which meant that the British heavily invested in its prosperity. The first full airconditioned building in south Asia was a colonial office building in Singapore (Chang & Winter, 2015). Sudan on the other hand, was colonized solely for political reasons, namely Kitchener's ambition to become viceroy of India, the desire to avenge the death of Gordon and the need to curb the Mahdist threat to Egypt (Home, 2013). It, however, held little economic value, which is why, despite Kitchener and Mclean's vision to turn it into a 'European utopia in Africa'(D'Errico, 2015), it remained severely underfunded and classed as a 'joint Anglo-Egyptian condominium' rather than a British colony (Warburg, 1970).

Though both countries currently struggle with AC reliance, the colonial backstory in Singapore meant that the association with ACs is more about productivity and status than it is about comfort (Chang & Winter, 2015), which impacts which solutions are suitable for that context.

The British carefully controlled settlement patterns in Khartoum and Khartoum North. Khartoum North was built as an industrial town and was similarly designed as a western city. The street clearly defined plots, and the allocation of these plots was decided by ballot, which hindered families from being nearby (Ahmed, 1978). Therefore, urban families lived independently from one another except for the occasional rural lodger. The British left Omdurman and the third-class native quarter in Khartoum for the natives to build as they pleased (Hassan, Elkheir, et al., 2017).

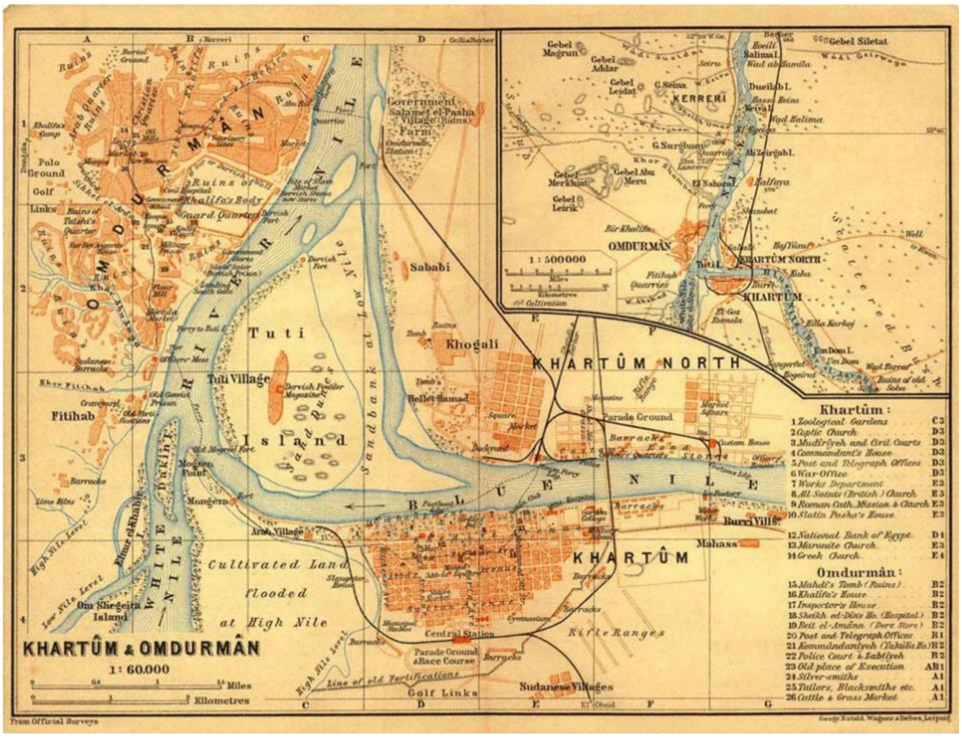


Figure 2.19 A map showing Khartoum, Omdurman and Khartoum North. Source: (Hassan, Kobylarczyk, et al., 2017)

The Mahdi had previously given his followers large swatches of land in Omdurman, allowing families to live together and expand organically (Hassan, Elkheir, et al., 2017). In Omdurman, the street is whatever space remained between the houses; thus, the house dictated the street form, which created the medina-style maze of organic plots. Figure 2.19 shows the three cities with Khartoum and Khartoum North's straight, square grid and Omdurman's organic structure.

The Traditional house

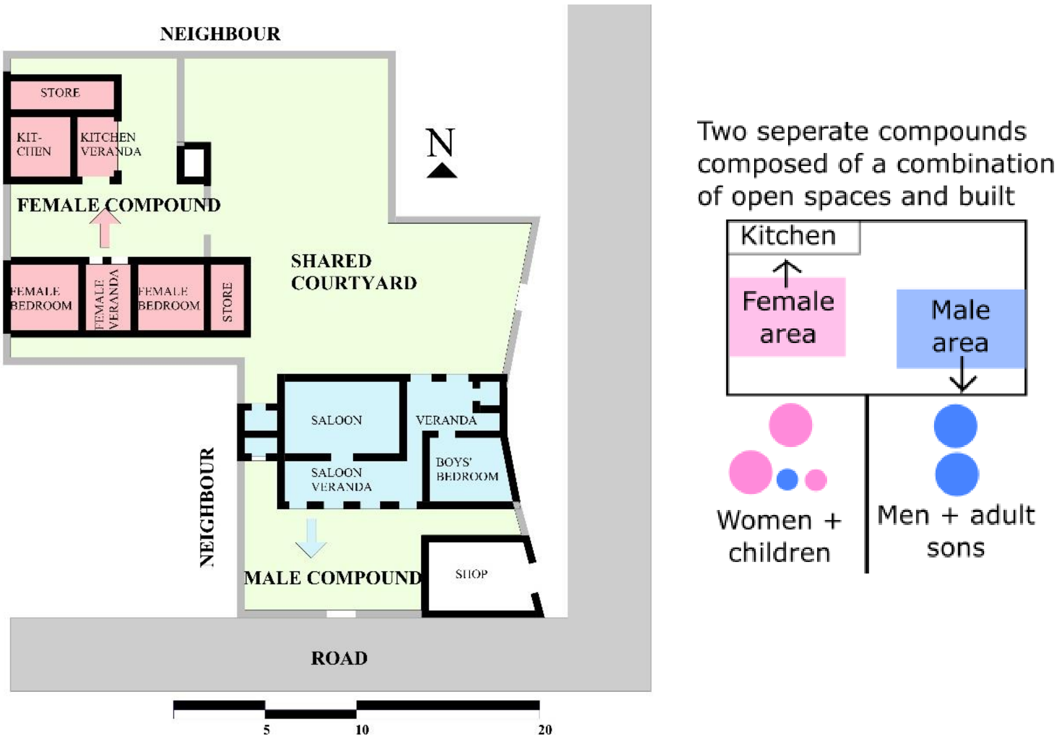


Figure 2.20 Left: A plan of the Traditional house. Edited by Author. Source:(Osman and sulieman, 1996). Right: Author's interpretation of the zoning in the Traditional house

The Traditional house was born from the unique urban conditions in Omdurman; it is the urban adaptation of the rural home. In Kenya, Muller called this process *'transferring rural socio-spatial characteristics into an urban environment'*(Muller, 1984a). Its close resemblance to indigenous architecture is why Osman named it the 'traditional' house. Most traditional houses were built before 1950 and were the second most prevalent type in the early 2000s. Most of them exist in unplanned neighbourhoods acquired by inheritance in Omdurman (K. M. Osman & Suliman, 1996). They are made with mud walls and timber roofs. The different generations contribute to the house's organic growth, which is why 90% of its residents said they were not involved in the house design. (K. M. Osman & Suliman, 1996) These houses do not have regular forms and are categorised by a scattered combination of built units and open spaces. They have 10-12 different spaces, including courtyards, verandas, bedrooms, bathrooms, toilets, and kitchens. Toilets are distinct from bathrooms in these households because they were built before advanced plumbing systems were available. Despite the social ties in urban centres being weaker than in rural areas, they are still significantly strong compared to western standards (Ahmed, 1978); thus the lifestyle remained primarily unchanged. They resemble the rural household because the male space is closer to the street and the female space is secluded and private (Figure 2.20). The two zones were segregated into two separate but linked compounds, each housing several scattered rooms and verandas. Families ate segregated in their respective male and female zones. The female courtyard is the main living space in this house type.

2.4. Urbanisation gives rise to the Institutional house

Figure 2.21 (Upper) The New Diems in the 1950s. Source: (Hamdan, 1960)

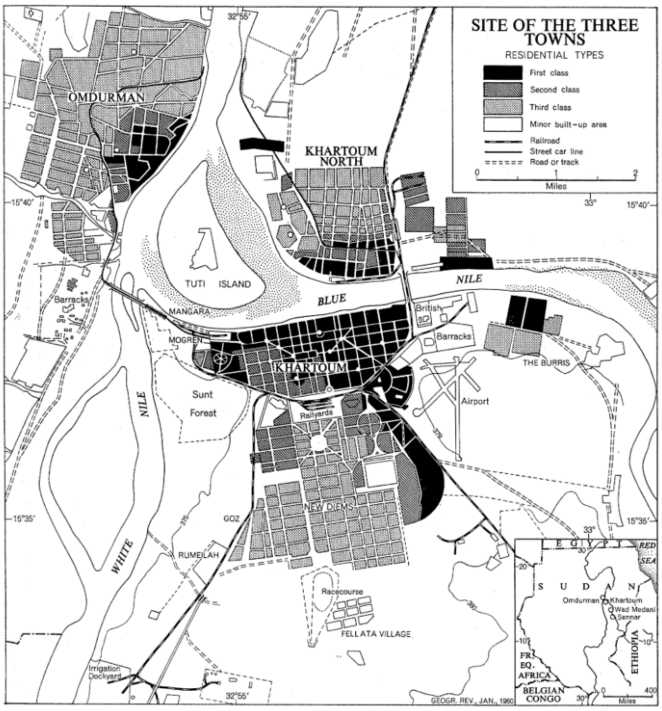
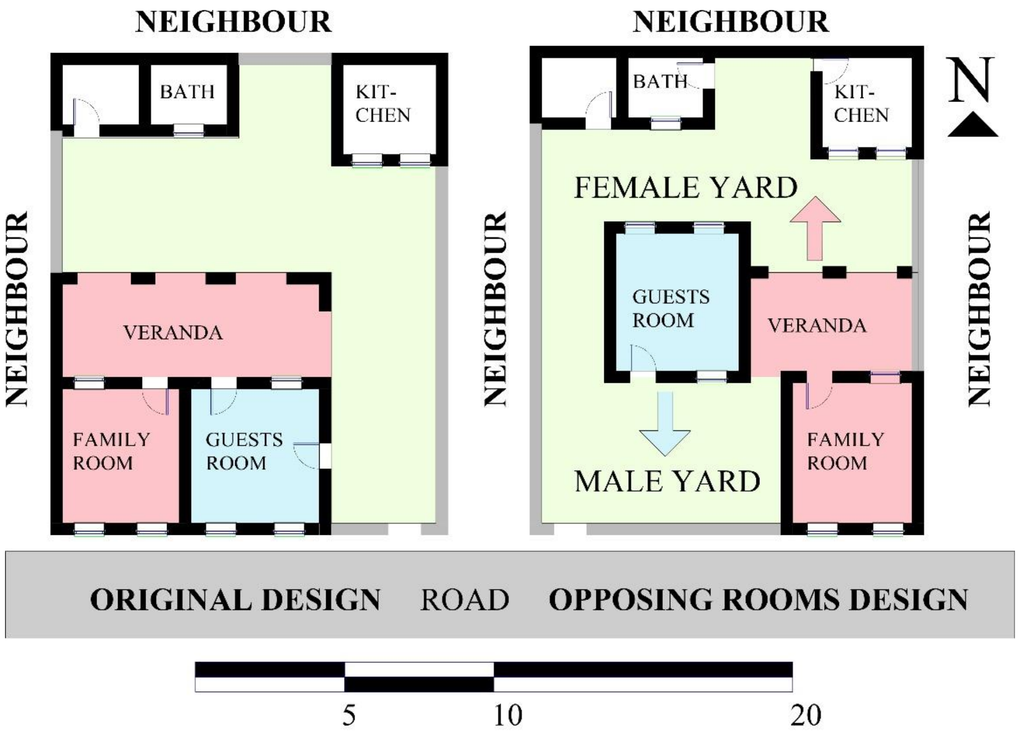


Figure 2.22 (Right) The replanned greater Khartoum in the 1950s

In 1945, attempts were made to re-plan Omdurman, where most natives lived, to make the streets more linear, but it was too difficult (Hassan, Elkheir, et al., 2017). The traditional Sudanese house required extensive space for courtyards, which is why many architects opposed reducing plot sizes in Omdurman (Elias, 1970b). In Khartoum, British nationals and foreigners still lived in spacious colonial houses in first and second-class plots. The third class area, the native quarter (the old Deims), started to grow in 1920. By 1949, it was overcrowded with plots ranging from

30-60 m2 (Satti, 2005). Figure 2.22 shows re-planned Omdurman, Khartoum and Khartoum north in the 1950s. Each tribe had its own 'Diem' or quarter. The government resettled these occupants in 1949 and moved them to the New Diems outside the railroad ring (Figure 2.21). It first conducted a social survey that ensured the new location was acceptable to occupants. They also maintained the social cohesion of the population by moving neighbours together. Each family had a plot of 200 m2 (Fawzi, 1954). Most natives during this time were servants and workers, so the government started to teach and train tribe elites to become civil servants at Gordon College (Afsar et al., 2016) This created the first native government employees (the Effendiya) and professionals, who later became the first formal middle class, as will be further discussed in Chapter 4 (Sahal, 1999).



The Institutional house

Figure 2.23 Initial design (left) and revised design (right) proposed by Fawzi with the opposing bedrooms. Source: (Fawzi,1954)

The government surveyor Fawzi needed to fulfil the social needs met by traditional houses within a small plot space and limited economic resources. (Fawzi, 1954) The initial design he proposed (Figure 2.23) to the locals was rejected because it did not create segregated sleeping areas, which was uncomfortable if a male guest slept over. The second issue was that the family area was exposed if a guest was in the guest room. Finally, the position of the kitchen and bathroom in relation to the main door was problematic. This is because women wore revealing and loose clothes indoors due to the heat; which would result in them being exposed to the public if the door was left open.

Fawzi then redesigned the rooms to oppose each other, creating two smaller courtyards instead of a large one. This created a male and female zone and satisfied their needs. Figure 2.23 shows the two proposals. Another proposal suggested creating a barrier wall between the male and female half. It got rejected because most families would likely live in one half and rent the other, recreating the overcrowded position. This demonstrates the importance of using past behaviour to predict challenges that future solutions might face.

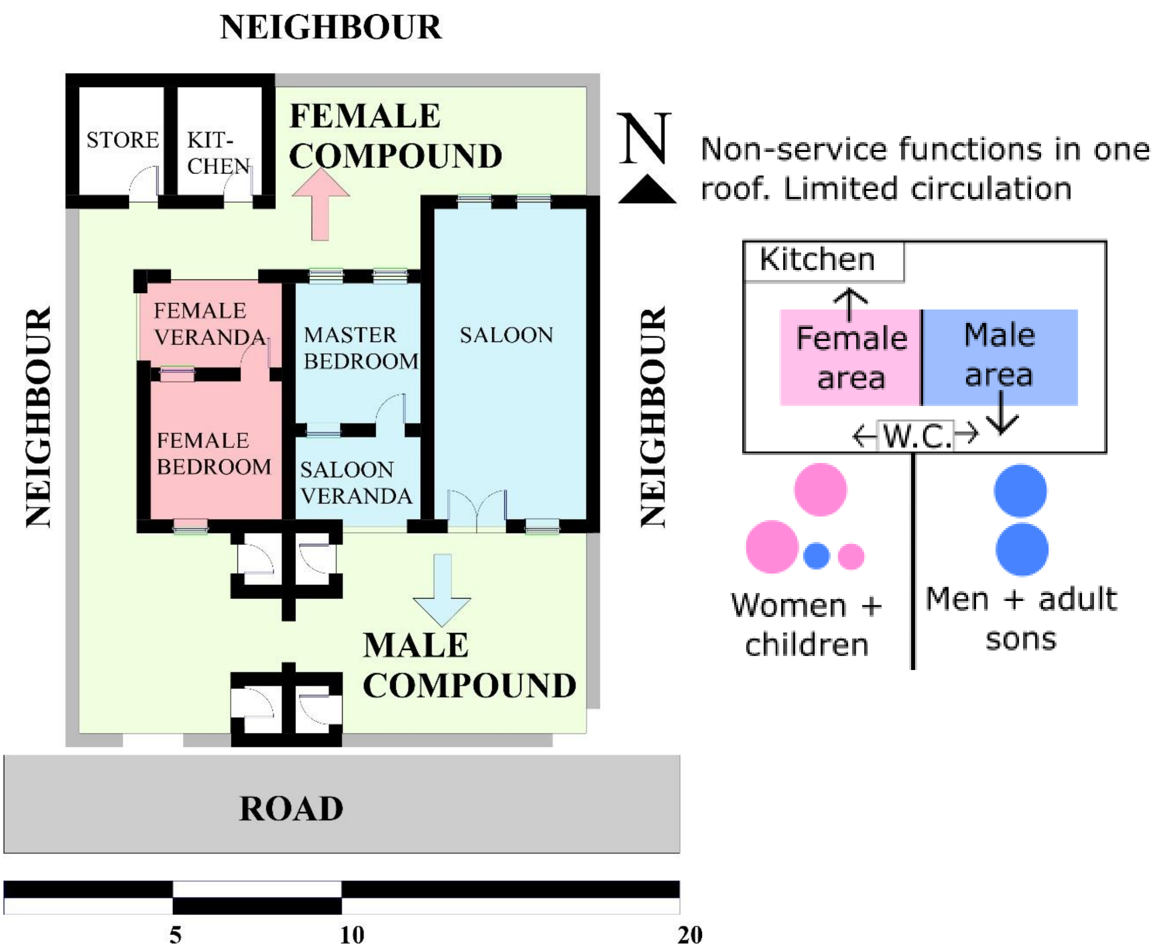
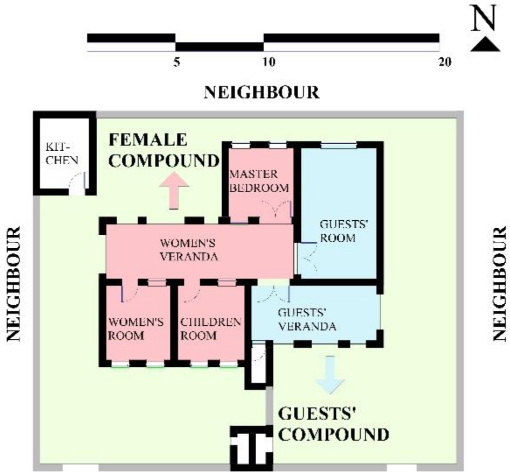


Figure 2.24 Left: Example of an institutional house. Source: (K. M. Osman & Suliman, 1996). Right: The Author's interpretation of the zoning in the institutional house

Fawzi's prototype became extremely popular even beyond governmental housing projects. It created a new topology called the institutional house; the name came because the original design was developed by the institution (government) (K. M. Osman & Suliman, 1996). Most of these houses were constructed between 1950-1960 when the government was building public housing before and after independence in 1956. In the early 2000s, it was the most prevalent type and mainly used by middle and low-income families in planned neighbourhoods. The roof is typically either corrugated iron sheets or timber. The walls are red bricks, sun-dried bricks or mud (K. M. Osman & Suliman, 1996). Because they are a condensed version of the Traditional houses, they have both less variety and number of spaces. For example, instead of a separate kitchen veranda and female veranda, there is only one female veranda to function as both. The families ate together on weekdays and segregated during weekends because of extended family members coming over. All the spaces are under one roof except for the kitchen and toilet, as shown in Figure 2.24.



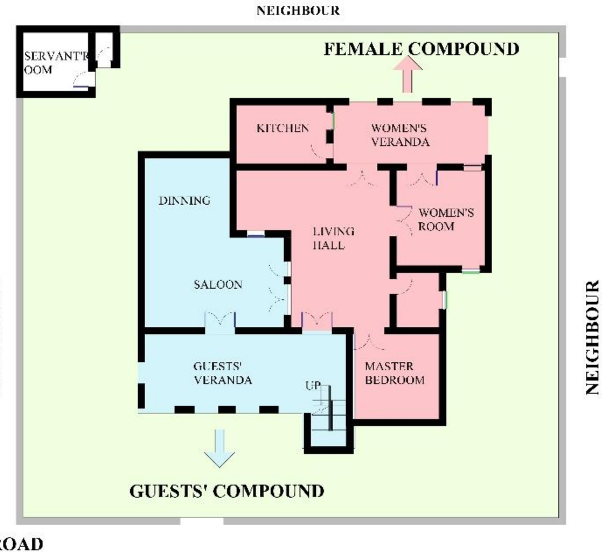


Figure 2.25 An example of middle-income family house inspired by the Fawzi's design. Source: (Ahmed,1978)

Figure 2.26 An example of upper-income family house inspired by the Fawzi's design. Source: (Ahmed,1978)

Figure 2.25 and Figure 2.26 showed how they followed government prototypes with some alterations. Elias surveyed a scheme of institutional houses (Elias, 1970b). He described a strong sense of community; the streets were packed during the evening. Groups of men sat together, drinking their tea and inviting passers-by whom they usually knew. Casual visits were common without prior arrangements. Word travelled fast, and community issues were discussed in meetings. Many residents visit their original birth villages for holidays and keep frequent contact.

However, they did not want to return to retire there. This shows that up until this point, the fundamental social features of the Sudanese home had not changed, despite the typology change.

2.5. Economic hardship exacerbates urbanisation leading to the Pragmatic house

Sudan gained independence from the United Kingdom in 1956, which was soon followed by the first civil war (1956-1972). The war, coupled with abolishing the passport act in 1922 (Pantuliano et al., 2011), which allowed for unrestricted immigration, brought the first wave of internally displaced people IDPs to Khartoum. Until 1959, 80% of Sudan's population was rural, and the government's policy of agriculture reform deterred immigration to urban centres, as people were already satisfied (O. M. Osman, 1959). The main driver for urbanism in developing countries is the search for better living conditions in cities compared to villages and the access to consumer goods associated with globalisation, such as mobiles (Leichenko & Solecki, 2005).

Three military regimes came after independence, each with its distinct agenda. The second military regime (1969-1985) was socialist and focused on creating an industrialisation boom in the 1970s and building homes for these workers. However, their focus was on Khartoum, believing that improving the centre will spill into the peripherals as 67% of factories were established there (Ahmed, 1978; Sarzin & Mehta, 2011). This attracted people to move to Khartoum in search of better job opportunities. To improve the economy, the second regime adopted IMF policies (1978-1988), which caused inflation that hugely impacted salaried employees. Therefore, many Sudanese professionals decided to immigrate to the Arab gulf, where there was an oil boom in the 1970s. 1983 marked the beginning of the second civil war (1983-2005) and a great famine, which led to another wave of IDPs migrating to Khartoum (Pantuliano et al., 2011). The majority of Khartoum's population was now internally displaced people. While many of these migrants returned when the conflicts ended (Ibrahim & Omer, 2014), they still constituted 24.2% of the population of Khartoum in 2011 (Sarzin & Mehta, 2011).

The pragmatic house

These small houses are illegally acquired in spontaneous neighbourhoods to house internally displaced people (IDP). They are like traditional houses but are built according to the household's ability and needs. As such, they have few spaces: the courtyard, the common room, the master bedroom, the toilet, the bathroom and the kitchen. The lack of segregation makes the house uncomfortable when there are guests. The majority were built during the 1970s and 1980s when mass immigration to Khartoum began. Families in this household are usually in the growing phase as they are parents with small children.

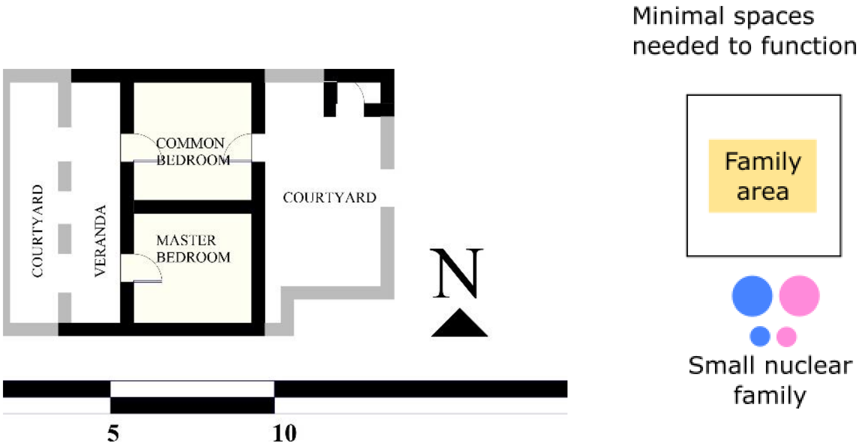


Figure 2.27 Left: Example of the pragmatic house. Source (Osman & Suliman, 1996). Right: The Author's interpretation of the zoning in the pragmatic house

2.6. An oil boom funds the contemporary house

When Sudan experienced its own oil boom in the 1990s, it overshadowed industrialisation, and oil accounted for 95% of exports by 2008 (Pantuliano et al., 2011). The third military (1989-2019) regime wanted to advocate modern Islam. Fuelled by the oil boom, they focused on creating an educated class and enrolling women in the workforce (Hale, 1996). They also aggressively reformed squatter settlements in Khartoum and invited investors to the city. These investors built gated communities and Dubai-style projects along the Nile. The impact of this economic progress will also be discussed in chapter 4. Due to this economic progress, Sudan's urban population grew from 8.3% of the total population in 1956 to 43% in 2008 (Sarzin & Mehta, 2011), with Khartoum's population bloating from 245,000 in 1956 to 7,000,000 in 2008. The expats who left in the 1970s started returning to Sudan, carrying the modern building ideals common in the

Arabian gulf (Elkhier, 2014; K. M. Osman & Suliman, 1996). For example, people now favoured modern Mediterranean-style villas over vernacular one-storey veranda houses (Bashier, 2008).

Sudanese society has been historically against female education and had a very traditional outlook on gender stereotypes (House, 1988). Women's role was in the house raising children; work was only allowed if needed and if the job was perceived as feminine, such as nursing and teaching (Darkoh, 1994). They were encouraged to embrace the Islamic tradition of staying home as much as possible. Based on official figures, in 2012, 30.9% of Sudanese women were part of the workforce (UNDP, 2013), up from 20.2% in 1986 (Darkoh, 1994). Although these figures under-represent women's actual contribution to the workforce (Darkoh, 1994; House, 1988), they can be used as an indicator of increased contribution. 28.6% of households in Sudan have female household heads, mainly due to absentee husbands migrating to urban centres leaving their wives to focus on agricultural work. This is evident because women in urban areas constituted just one-fifth of the female workforce.

The circumstances of upper- and lower-class urban women differ. Women in upper-class urban areas are more involved in formal employment, whereas urban women of lower class work mainly in petty trade, like selling food out of necessity (Darkoh, 1994). This is due to educational differences, location and family background (Darkoh, 1994). In Khartoum, women constituted 55% of students enrolled in higher education in 2008 (World Bank, 2012). As women became more educated, they had fewer children due to the cost of childcare and increased awareness (Darkoh, 1994). This reflects that the family structure between urban upper and lower classes differs depending on how 'modern' the family is. As a result, the type of household needs would differ as well. Educated employed women are also more likely to use their supplementary income to increase the family's living standards (House, 1988). It could be speculated that this will increase the number of families who become middle-class families.

Employed women devote any available time lost to working hours to family demands rather than leisure (Mattingly & Bianchi, 2017) This reduces the time available to spend on social activities like drinking tea, chatting in the yard, visiting neighbours etc. This could have a large impact on the lifestyle of Sudanese families as many activities, such as sleeping in the yard and cooking on the veranda, were social activities in addition to chores, as mentioned previously.

Women's economic independence in West Africa allowed them to become independent from their families and in-laws (Alber et al., 2010). This strengthened the spousal relationships (the nuclear family) at the cost of other familial relationships. In Kenya, kinship ties are also weakening as result of urbanisation. Women with 8:00 to 5:00 jobs in the formal sector opt for domestic workers as an alternative to extended family childcare. (Muasya, 2016) This trend can also be seen in Khartoum with au pairs used for childcare. *'the trend toward modernity has been captured in the gradual transformations of African marriage and family organisations away from corporate kinship and extended families toward nuclear households.'* (Bigombe & Khadiagala, 2004, p. 2)

Urbanisation, migration and population growth on limited land space have also reduced extended family prevalence (Kazianga & Wahhaj, 2015) (Muller, 1984b) Eight out of nine African countries in a 2015 study saw an increase in nuclear households from 1990 to 2013 (Kazianga & Wahhaj, 2015) A study in 1970 found that around 50% of houses are separate (nuclear), 20% patrilocal and 30% matrilocal (Abdelrahman & Morgan, 1987).

Modernity prioritises nuclear familial ties to extended ones (Murphy, 2008). This suggests that families that are more modern are more likely to live in nuclear households. In the case of Khartoum, that would mean upper urban areas were more likely to live in a nuclear family setting. However, this could also be an upper-floor apartment or a separate extension to the main family household. Another possible implication of these weakened ties is reduced social visits from extended relatives. These modern family characteristics are important as they shaped the form of the contemporary house.

The Contemporary House

The contemporary house is a villa-type residence with one or more floors and typically designed by an architect. In 1993, it was the least common in Omdurman, with the bulk built in the 1970s and 1980s (K. M. Osman & Suliman, 1996). Contemporary houses usually have concrete frames with red brick walls. They feature the addition of the hall, the guest bedroom and the guest bathroom and do not have saloon verandas. Children sleep in a 'children's room' and parents in a 'master bedroom', highlighting the new focus on the nuclear family. These houses are more akin to western detached houses as functions are all under one roof rather than scattered spaces like the other house types native to Sudan.

This means that kitchens are now part of the building. The kitchen was separate in the past because it was shared with other families, and now the modern independent family has different needs (Elias, 1970b) Families in contemporary houses usually have wealthy household heads and less segregated homes that bring the family together rather than separate it (K. M. Osman & Suliman, 1996).

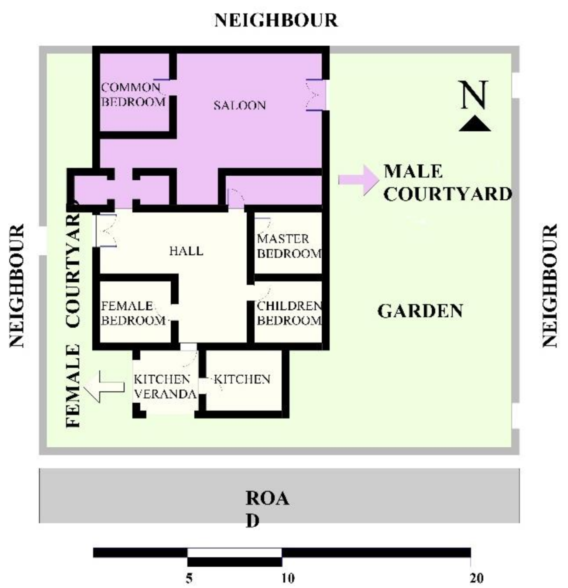


Figure 2.29 An example of a contemporary / detached house

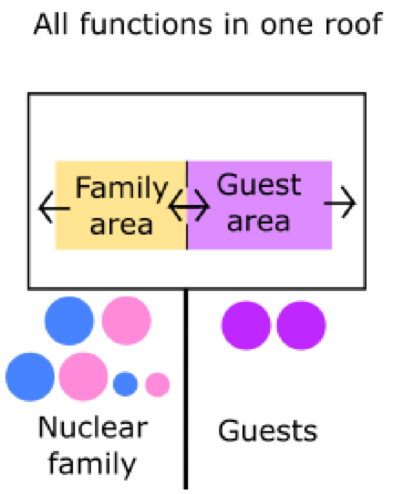


Figure 2.28 Author's representation of the zones in a contemporary house

As shown in Figure 2.28; the house is mainly divided into family and guest areas that are linked together. The family eats all meals together, usually in the living room/hall and spends their daytime there as well (Mohammed & Kurosawa, 2005). The only outdoor events are receiving guests in the evening in the garden and cooking on the veranda when there is an excess demand, like Ramadan or Fridays (K. M. Osman & Suliman, 1996). Despite these families spending most of their time indoors, 83% of respondents believed a yard space was necessary (Mohammed & Kurosawa, 2005).

A study in 2005 called them 'detached houses' (Mohammed & Kurosawa, 2005). They found that the exact arrangement of spaces differed significantly but could be grouped into 6 major arrangements. The general trend showed that from 1970-2003 the houses showed less adherence to segregation and more western culture brought back by educated individuals. This resulted in the kitchen being close to the guest room for easy service. The guest room still has its own bathroom to reduce guests' need to enter the female side. The houses still mostly had two entrances for males and females. The study found that most respondents refused to live in apartments because of the need for a yard; it recommended that large balconies could help replace yard spaces.

2.7. A comparison between the house types

The previous sections looked at the details of each typology, comparing them together helps reveal the bigger picture of lifestyle evolution and how it affected design of housing types. Figure 2.30 shows how the Sudanese house's morphology changed as it transitioned from rural to contemporary. The family structure shifted gradually from a highly social community to a nuclear-based family. In the rural setting, the extended family structure is composed of several families living a communal lifestyle, similar to a small village. The segregation during the day is gender-based, with the women using the kitchen and the men using the diwan predominately if they are at home. However, at night, each family has their own private room and courtyard to store their belongings and sleep. Due to polygamy, some family units could be one of

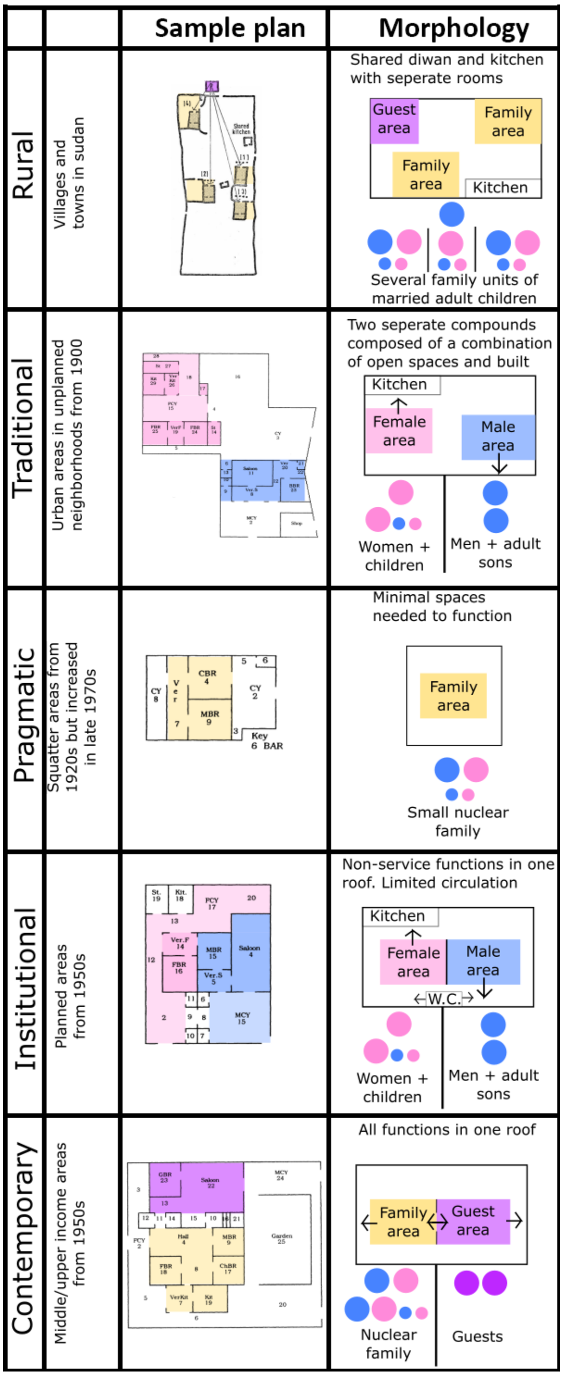


Figure 2.30 The morphological change as the Sudanese house transitioned from rural to contemporary

the wives with their children. In the traditional setting, the families act more like one large family with attachments rather than several closely related families. It could be one nuclear family where the household head is a single couple, but several lodgers and unmarried adult children need to be segregated, which is why the division is more gender-focused rather than family-focused. The large space allowed for two separate compounds, and the distance between those compounds emphasises the strength of that segregation. In the transition from traditional to institutional, the lack of space decreases the distance between the two compounds, and so facing different directions becomes the alternative to create that segregation. The family structure is still similar to the traditional one. Finally, in the contemporary context, only one single nuclear family occupies the house. As they are all related, only guests need to be segregated. Any extension to the family is housed in an entirely detached unit with no shared spaces.

Table 2.2 The transition of behaviors from rural to contemporary

	Rural	Traditional	Institutional	Contemporary	Change
Eating arrangements	Household heads in diwan while women and children eat together	Family eats seggregated into male and female groups	Family eats together on weekdays and seggregate on weekends	Family eats together everyday	Less gender seggregation
Living area	kitchen area	Female courtyard	Female verandah	Hall	More enclosed
Sleeping arrangements	Each family in their courtyard	Females in FCY Males in MCY	Parents + small children in FCY Adult males + guests in MCY Adult females in FCY	Parents in Master bedroom Children in child bedroom Guests in guest bedroom	More privatization
Social activity during chores	Social activity	Social activity	Chores	Chores	Less socialising
Use of rooms	Rooms for siestas and storage	Rooms for guests, siestas and storage	Rooms for guests, siestas and storage	Rooms for sleeping	Specialisation of function Extended usage hours

The transition of behaviours from traditional to modern was also gradual, with each stage changing 3 or 4 features. Table 2.2 summarises the changes in eating, living, sleeping arrangements, socialisation during chores and the function of rooms. The eating and sleeping arrangements became less gender-segregated and more family oriented. The living space became more enclosed, and rooms now catered to sleeping indoors, which extended its use rather than being used intermittently. Both these trends reflect the increasingly internal lifestyle. Finally, chores no longer became an activity that accompanied socialisation, but rather a task to be completed, reflecting the reduced importance of socialisation.

2.8. Conclusion

In the introduction section 1.1 it was mentioned that vernacular architecture adapts to slow change. This is a key factor in its success in meeting both sociocultural and environmental needs. This chapter has demonstrated how this unfolded in the Sudanese house in its recent history. It transitioned from a collection of scattered rooms into a detached house. This was a response to the household structure gradually changed from a social extended family setting with strong gender stereotypes into a private nuclear one with working parents. These changes have impacts that are evident even at the space scale as seen in the evolution of the Rakuba into the hall. With each stage, the space became more closed and secluded than the last. Another key transition was from the outdoor to indoor life. This is evident in the main family space changing from the female courtyard (outdoor) into the female veranda (semi-outdoor) and, finally, the hall (indoor).

The rise of these nuclear households means the 'Haboba' has a reduced ability to influence younger generations and instil traditional Sudanese social values in them. In an era of globalisation and mass media, this could further encourage embracing modernity, which along with urbanism, is at the heart of this change.

When cities expanded, the Sudanese family carried their culture from rural areas. When faced with decreasing land size and economic challenges, they needed to adapt their lifestyle into a new mould, which created the institutional house. A decade later, mass immigration and IDPs created the pragmatic type. The contemporary house appeared around the same time, which suggests a social juxtaposition due to a large class divide (K. M. Osman & Suliman, 1996). The contemporary house was born out of a cultural shift rather than necessity as the last three house types. It represents a leap compared to the other three types where transitions were more gradual.

The oil boom ended in 2011 with the succession of South Sudan, taking away 75% of the oil fields. This has slowly led to an economic crisis that peaked in 2018 and is still ongoing. The economic crisis, combined with the frustrations of the newly educated middle-class, led to a revolution in 2019 that marked the end of the third military regime. Expats, who are usually unaffected by the fluctuations of the Sudanese economy, have started returning to Sudan in larger numbers since 2017.

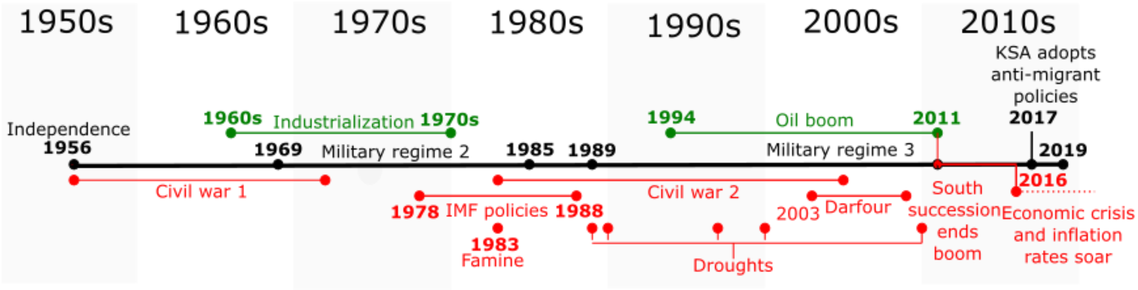


Figure 2.31 Summary of the major historic events from the 1950s till today. By Author

Figure 2.31 summarises the main events from the 1950s till the 2010s, highlighting the positive events in green and the negative ones in red. It reflects that, as with most developing countries, progress was usually in the form of 'short periods of accelerated growth' rather than ten years or more of sustained growth (Birdsall, 2010). It is also usually triggered by a shock-positive event (Birdsall, 2010). These are features of unsustainable development that will be explored further in chapter 4.

Chapter 3 Methodology

This chapter focuses on explaining the methodology used in the research to answer the questions raised in the introduction and the gaps found in the literature review. It will start with an overview explaining the overall strategy and justification for it. It will then outline the research design that underpinned the study and how it was practically applied. Finally it will go into the technical details of each method used both theoretically and practically. The methodology will be further reflected on in the conclusions chapter, to illustrate how it can be used by other researchers working with sociotechnical built environment research in developing countries.

This study looks at the drivers of unsustainable development in Sudanese housing from several different angles. The multi layered scope encompasses the urban level and the building level and includes the historic, socioeconomic and technical/ climatic aspects of those two levels. The challenges of working in a developing country with limited documentation add another layer of difficulty. A single methodological approach would not be able to fully capture the complexity of the research. This is why the researcher used a multi-layered methodological approach to cater to the needs of each context. Though the approach provides flexibility to analyse case studies using different tools, it needs to be detailed and thorough to ensure the validity of the data and its replicability.

The complex methodology used in this study is similar to the Case study method CSM used for socio-scientific research of building performance by the FLASH team (Facilitation Learning and Sharing) (Cooper, 2018). The FLASH programme aimed to understand the outcomes of low energy retrofits of a social housing project from a social technical perspective, a more advanced form of post occupancy evaluation. The FLASH team was comprised of a physicist, a social scientist, an architect and two engineers to reflect the different aspects covered in their methodology. They used a pilot project to outline the types of data needed, the methods each one required and the optimal sampling strategy for the development. After conducting physical building monitoring and occupant interviews the data from the two sources was co-verified to compensate for any inconsistencies created by any one methodology.

This research similarly used a pilot project followed by an extensive study and then analysis and verification. The author's initial 2018 study and subsequent pilot study can be considered exploratory research methods. They both sought to generate initial ideas about the phenomenon and measure its extent. Exploratory research does not always lead to an accurate understanding of the problem but it defines its scope and nature. The full-scale study falls under the category of both descriptive and explanatory research. Descriptive research focuses on detailed observations and recording of phenomenon while Explanatory research aims to understand a phenomenon's causal factors and outcomes (Bhattacherjee, 2012). The descriptive part answers the what, where and when as the explanatory part focuses on the why and how. Combining the three types and understanding their scopes is needed to ensure a holistic understanding of a problem.

3.1.Research design

The methods used in a research can be considered tools. However, these tools can be used differently depending on the required outcome. Research design focuses on how these methods are combined and implemented, like a master plan. This research used a combined ground theory-abductive strategy and the reasoning that led to this choice will be explained in this section.

'The research design is the plan or strategy researchers use to answer the research question, which is underpinned by philosophy, methodology and methods' (Chun Tie et al., 2019, p. 1).

Research can be inductive, where the researcher uses data to build a theory or deductive, where the researcher has a hypothesis and collects data to test it (Bhattacherjee, 2012). The choice depends on the researcher's experience and field. Inductive research is more suitable when few explanations are available, while deductive research works best when conflicting theories exist on the same subject. The limited data available on thermal comfort data in Sudan favoured an inductive approach.

Among the inductive research methods is the grounded theory. *'Grounded theory (GT) is a research method concerned with the generation of theory, which is 'grounded' in data that has been systematically collected and analysed. It is used to uncover such things as social relationships and behaviours of groups, known as social processes.'* (Noble & Mitchell, 2017, p. 34)

The original designers of the theory, Glaser and Strauss, believed that after data has been collected, its analysis can generate theory, which would then guide the researchers' further analysis and focus. This is called theoretical sampling. Rather than just using the data to produce a theory and stopping there, which is where a typical inductive process ends. Noble gives an example where a researcher asked open questions about patients' experiences with heart failure. The interviewees frequently cited errors during surgery, which prompted the researcher to focus on that as the new main topic (Noble & Mitchell, 2017). The researcher in Noble's case chose the ground theory method because previous works focused only on physical, quantifiable criteria and did not account for other social or psychological aspects (Noble & Mitchell, 2017). This is similar to the problem faced in this study, as most current works on thermal comfort focus on reaching a quantifiable thermal comfort temperature and less on understanding the accompanying socioeconomic aspects or drivers. Another advantage of the method is that the author's previous 2018 study creates a pool of data to start with and create an initial hypothesis. The author is also familiar with the context, making theoretical sensitivity more accurate. Theoretical sensitivity is the ability to decide which pieces of information are important and is a key component in deciding which leads to follow (Chun Tie et al., 2019).

The ground theory's main flaw is its rigid requirement for theories to emerge in a purely inductive manner (Timmermans & Tavory, 2012). It necessitates approaching data without any preconceived conceptualisations or a theoretical framework (Noble & Mitchell, 2017). The abductive approach is a pragmatic approach (Timmermans & Tavory, 2012) that is more flexible as *'it can explain, develop or change the theoretical framework before, during or after the research process'* (Kamal, 2015, p. 29). This helps with jumping back and forth between different types of data. Combining the two methods was advocated by Charmez as part of a constructivist ground theory (Timmermans & Tavory, 2012).

3.2. Application of the research design

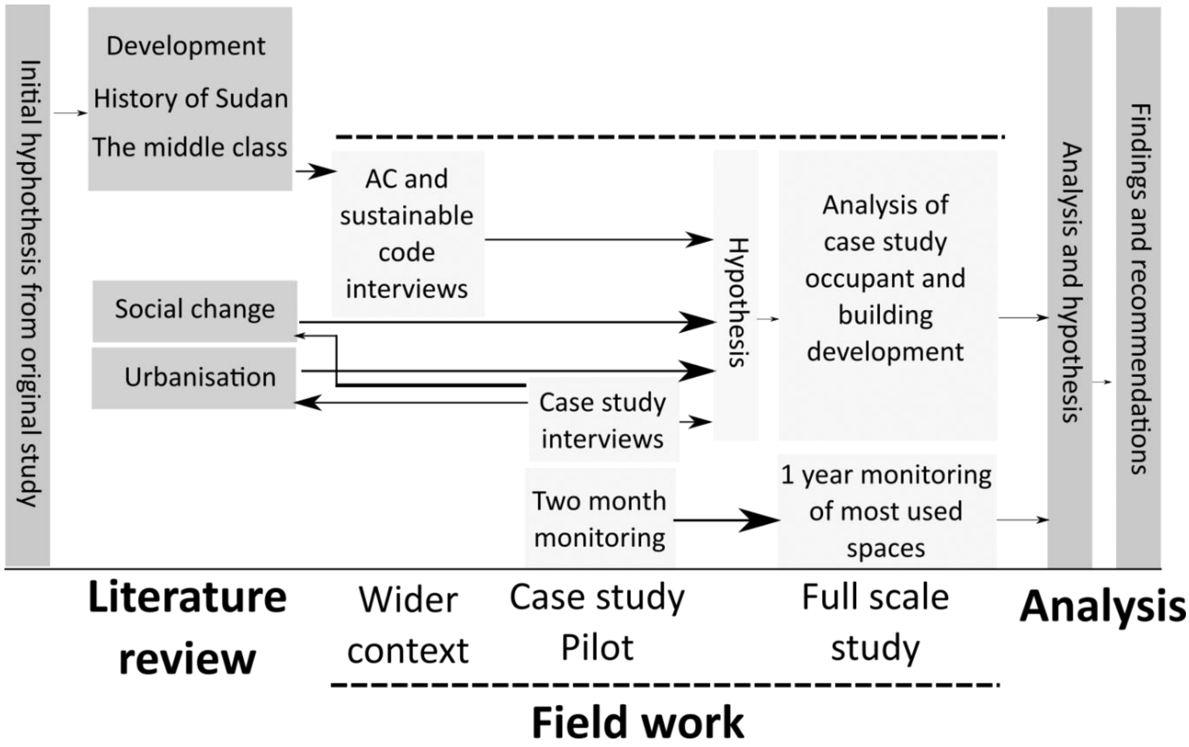


Figure 3.1 Research design

Figure 3.1 shows how the combined ground theory-abductive strategy was implemented in the research. It used a combination of the qualitative methods such as interviews and case studies and qualitative building monitoring in addition to frequent literature reviews.

The author's initial literature review focused on creating a historic and socioeconomic background about Sudan and developing countries. Data was scarce on two key themes: The history of AC adoption in Sudan and the current problems facing architects regarding sustainable construction. Therefore, a series of interviews were conducted with industry professionals in 2020 to understand these issues. Among the trends these interviews highlighted, were poor economic conditions that encouraged densification. This led to a literature review on the urbanisation trends in Khartoum. This review was also guided by comments made by the case study interviewees, who mentioned how the city 'changed' and the mass urbanisation led to weaker social ties and security issues. The case study interviews also highlighted social change as a critical factor, which led to its addition in the literature review. As the theory developed, the researcher conducted additional interviews to fill gaps and check interpretations. In addition to this co-verification, the interviews helped progress the theory, which is theoretical sampling.

Four case study buildings were monitored in 2020 for 2 months to help create initial hypotheses about how the buildings worked and which spaces were the most used. This was the pilot project. It allowed the author to test the equipment and identify the most optimal settings that could help verify the hypothesis made. This led to a full year-round monitoring period. After the monitoring and the analysis of the development led to more refined hypotheses, it was used to guide the research findings. Going back and forth between different stages helped guide the researcher through the multidimensional concepts interacting at different scales.

3.3.Sampling

'Sampling is the statistical process of selecting a subset (called a "sample") of a population of interest for purposes of making observations and statistical inferences about that population.' (Bhattacherjee, 2012, p. 65) Good sampling practices require identifying who the target population is, what sample size can represent them and the most suitable sampling technique. Probability sampling randomly selects participants and is generally considered more reliable than nonprobability sampling. However, due to the restrictions of the study, a combination of different types of non-probability sampling was used. For the case studies, convenience sampling was used, as the study required extensive communication and involved expensive equipment. Therefore, the respondents had to be familiar with the researcher to ensure reliability and consistency. Expert sampling was used in the wider context interview, as the information needed is undocumented and not widely known to the general public.

3.4.Research methods

This section details the technicalities of the methodologies used, the justification of how they were used and the challenges faced by the author in implementing them.

Qualitative research

Qualitative research explores social phenomena by either analyzing the subjects directly, their interactions or traces of their experiences captured in documents. Its about understanding how things work in real life, beyond research settings (Kvale, 1996). Its flexibility helps researchers build their initial hypothesis and change it as new information emerges. The generality of findings from qualitative research can then be tested using quantitative research. This is called mixed methods research. For example, Steinar Kvale was researching how students felt towards grades, and one student mentioned in the interview that grades measure how much you talk and how much you agree with the teacher. Kvale's then used a questionnaire and confirmed that many students only agreed with the first statement.

The qualitative methods used in this study are Surveys and Case studies. The program nVivo was used to analyse all the qualitative research data as it provided an structured platform to host the different types of data. The main themes being explored, such as people's behaviour and economic issues, were predetermined and coded into the program. However, new themes were added as more data emerged.

Interviews

In his book 'Interviews: an introduction to qualitative research interviewing', Kvale describes interviews as *'a conversation with a structure and purpose'* (Kvale, 1996). In order to gain reliable information, its crucial that the questioning and listening are carefully planned and executed. There are many types of interviews. Informal interviews are spontaneous and have no guides or predetermined questions. They allow respondents freedom of expression because they resemble a normal conversation. In this study, this type of interview was combined with participant observation to explore themes as they emerged during the fieldwork. For example, during the frequent visits the researcher noticed different seasonal occupancy patterns in two unconditioned bedrooms. Through a conversation with the occupants, it emerged that the high temperatures make them choose to occupy the room fully in the winter and for limited hours in the Summer. If they had they been asked in a formal interview if they have different seasonal uses, they may have not recalled or noticed this change. Semi-structured interviews have a few predetermined questions and use guides to probe further for information. However, they contain open-ended questions that allow the respondent to decide what information is relevant to the answer. The interviewee can proceed to the next question or decide to probe further into the previous answer. Most interviews used in this study were semi-structured to help build and shape the researcher's initial hypothesis. A sample interview guide was added to appendix A.2. To ensure the respondents understood the questions, the researcher's questions were broken down into simple statements using everyday language. For example, instead of asking respondents: what are the future developmental plans for your family? The question was broken down into simpler ones asking where their children plan to live in the coming years and if they plan on making any changes to their house. Visual aids were also used to document the information during the interviews as shown in appendixes A.5, A.6 and A.7. This helped the interviewees confirm or correct any information.

Interviews pose many ethical questions that need to be addressed. The most important is the interviewees consent and data protection. In this study, the participants were asked whether they want identity to be disclosed in the study or not. They were informed that they are able stop the interview if they wanted to. Care was taken not to include any questions that could invade privacy or cause distress. This is especially important in the context of Sudan as a conservative society. All interviewees were debriefed at the beginning of the purpose of the interview and asked at the end if they have any questions or concerns. Two participant sheets are added in appendix A.1 and C.1 as part of the ethics application. The interviews contained factual questions to obtain information, narrative questions to document the houses and occupant history and discursive questions to discuss and clarify the interviewees' opinions. The researcher did the transcription in an intelligent, verbatim style, meaning the verbal fillers and repetitions were removed to make reading more manageable. A sample of this transcription is in appendix A.3. Interviews were held with different types of experts for the wider scope information and with the occupants for the case studies. They are labelled as shown in Table 3.1.

Table 3.1 Interview guide

	Interview	Interviewee	Title/ workplace	Date
Wider context	**AC expert 1**	AC industry expert with academic background	Division head at AC distributor 1	03.03.2020
	AC expert 2	Mechanical engineering lecturer	University of Khartoum	08.03.2020
	AC expert 3	Architect specialising in passive design and mechanical ventilation	Sudan university of science	11.03.2020
	AC expert 4	AC industry expert with experience in Sudan and the Arab gulf	Division head at AC distributor 2	15.03.2020
	AC expert 5	AC industry expert	Employee at an AC distributor 3	15.03.2020
	Civil servant 1	Architect and civil servant	Division head at ministry of planning in Khartoum north	15.03.2020
	Civil servant 2	Architect and civil servant	Head of division at a ministry of planning in Khartoum	31.03.2020
	Civil servant 3	Architect, civil servant and academic	Committee member of the sustainable building code	01.04.2020
	Architect 1	Architect	Employee at architectural office	30.03.2020
	Architect 2	Architect	Freelancer	13.04.2020
Case studies	**T1**	Three adults and three teenagers in the house	Traditional house 1 resident	14.03.2020
	T2	Two adults in the house	Traditional house 2 resident	30.01.2021
	T3	Two adults in the house	Traditional house 3 resident	31.03.2020
	M1	Two adults in the house	Modern house 1 resident	14.05.2020
	M2	Four adults and one teenager in the house	Modern house 2 resident	21.03.2020

Case studies

'Case research, also called case study, is a method of intensively studying a phenomenon over time within its natural setting in one or a few sites.' (Bhattacherjee, 2012, p. 93) It uses various methods to collect data, including observations, interviews and logs. It was chosen for its ability to provide a deeper context for phenomena within its natural setting. It captures more points of reference which helps understand the wider trends rather than focus on the daily occurrences, like the overall climate rather than daily weather. Lowe et al.'s paper encouraged the use of the Case study method as it '*..is capable not only of producing primary empirical data to support modelling and design but also of capturing the contextual complexity that is often required for causal inference* (Lowe et al., 2018, p. 474). Its problem is that many variables are uncontrolled, unlike in an experiment where only one variable changes at a time. This makes generalisation difficult for any findings found in the case studies into other contexts. In order to increase accuracy, triangulation was used to confirm findings. For example, to understand usage, the occupants were first asked about it in the interviews. The researcher also observed the usage; for example, rooms that seemed dusty are likely to be used less frequently. Finally, a logger was installed in the most used rooms. This was an AC logger for the conditioned rooms and a motion detector for unconditioned rooms. The data from all these different methods helped pinpoint the usage patterns. After conducting a within-case analysis where patterns were identified in each case, cross-case analysis was conducted to compare the cases.

As shown in Table 3.2, five buildings were used as case studies and were chosen to represent various family and building types. The specific selection criteria will be discussed in the case study chapters 5 and 6. The younger and older members of the family were interviewed. The courtyard houses were labelled T for traditional, and the concrete houses were labelled M for Modern. Initially, the study included only four buildings, but as T3 could no longer maintain the monitors, an additional case, T2 was added. T1, T3 and M1 have been previously used in the case study in 2018.

Table 3.2 Details of the five case study buildings

No.	House type	Family type	AC type
T1	Courtyard	Upper-middle income locals/ extended	Evaporative
T2	Courtyard	Lower-middle income locals/ extended	Evaporative
T3	Courtyard	Lower-middle income locals/ nuclear	Evaporative
M1	Multi-story	Upper-middle income expats returned 20 years ago / extended	Split units
M2	Multi-story	Upper-middle income expats returned 3 years ago / nuclear	Evaporative

Thermal images were taken in the case study houses using a thermal camera. The images were taken at 12:00 pm (noon) and 5:00pm (near sunset). The two images were compared to understand how the different surfaces accumulated heat throughout the day. Flir tools app was used to find out the exact temperature of different parts of the picture. The average temperature of the roof, walls, windows, and AC openings were taken. The walls were always the coolest part of the building and were used as a benchmark to compare the amount of infiltration from the roof, windows and AC units.

Quantitative research

Quantitative research focuses on numeric data, which in this study was obtained through the building monitoring. Descriptive analysis was used to describe constructs and their associations (Bhattacherjee, 2012). Excel was used to analyse the data as the analyses needed were simple and the researcher had prior experience using it in a thermal comfort study to produce visually appealing graphs. For the building monitoring, the data was first inserted into a main template (see appendix B.1), then separate excel files were linked to it. Each file was dedicated to a specific comparison, such as usage in different rooms or temperature changes with AC use.

Building monitoring

Pilot study

The case study buildings were monitored for a pilot study in 2020. Initially, the limited budget only allowed three houses to fit with internal temperature data loggers. The temperature data loggers were attached at 1.5m height on an internal wall away from the AC stream or the window that may impact the readings. Some of the data loggers were manufactured by the company Tiny tag, while the remaining data loggers were from Hoboware.

Figure 3.2 To the left, a photo of the Hoboware data logger. To the right, a photo of the Tiny tag data logger. Taken by the author

As mentioned previously, the sampled houses were picked based on logistical and security preferences. The temperature data loggers recorded the operative temperature and humidity every 30 minutes for three months, from March to May. An external monitor was placed on the balcony of the first floor of M1 because it was the safest outdoor spot available, as burglaries are common in Sudan.

Figure 3.3 The installation of a kWh logger and state logger in a split unit. The circle shows the data logger with the wire attached to the split unit's fins. (Middle) A close up of the logger. (Right) The wire with the forked end

Monitoring the AC use was not as straightforward as the thermal monitoring and required significant adjustments to each context and monthly check-ups to ensure the data was reliable. The evaporative coolers had motors for the pumps inside them. This meant they could be monitored using motor loggers from Hoboware. It was noted that sometimes the logger did not pick up the signal for a few days. Therefore frequent checks were conducted to recalibrate the logger and any missing data was flagged to make sure it did not impact any assumptions in the calculations. Split units do not have vibrations as they rely on a compressor, but their fins open and close (see the circle in Figure 3.3), a motion that can be monitored through state loggers from Hoboware. The state logger comes with a wire that is supposed to be attached to the AC's wiring to monitor pulses; however, that was invasive and would require a professional to install and remove it. The wire forks into two sections (Figure 3.3), and the author realised that they also log a pulse whenever they physically touch, so the author taped each end on a fin. When the fins closed, the logger read that as one or on, and it would detach when the fins opened again. This required inversing the numbers later in the data processing as the number one actually meant the fins were touching, and the AC was closed. When the power cut and the AC was already on, the fins remained open, giving a false indication that the AC was running. Therefore, the AC was considered off whenever the Carbon logger suggested a power cut was ongoing.

Another problem was that the wires were thin, which meant they could miss each other when the fins closed. Therefore, the author attached aluminium sheets to the wires to expand their surface area and ensured the surface was smooth enough that it would detach smoothly when the fins opened. The author stayed for at least 6 hours in each home, observing the occupants' behaviour and checking that the loggers worked without issues.

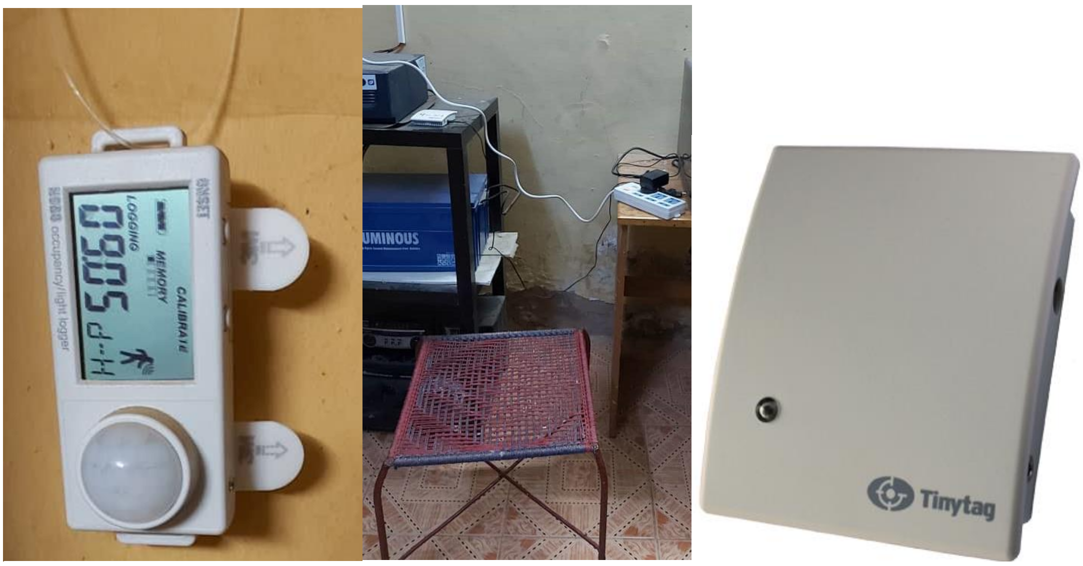


Figure 3.4 Left: A photo of the PIR Hoboware logger used showing it had detected motion. Middle: the carbon logger installed in the case study T1. Right: a photo of the carbon logger

Among the needs identified was a way to log usage for unconditioned rooms. A PIR logger uses infrared rays to log every time a user passes the logger's field of view. However, sometimes they miss the presence of a person in a room if they stay still for a long period, like when watching TV. Finally, a need arose to log power cuts because they became so frequent that they affected the users' usage patterns. For example, the AC loggers could indicate that the residents rarely open the AC at noon, whereas it may be simply because that's when power cuts are frequent. To log them, a carbon dioxide monitor was used. This logger is connected to the main power and registers zero every time the power does not reach it. The carbon dioxide levels it logs could be used to indicate space usage, but this was not relied on independently as has a very low accuracy. This is because the particles per minute levels that indicate the room is empty or occupied differs in each room based on the ventilation rates. A well-sealed room would have a high carbon dioxide level even with just one occupant, while a room with good ventilation would have a lower carbon dioxide level for one occupant. The carbon dioxide loggers are also sensitive to ventilation changes from opening vents, windows or doors.

Figure 3.5 Left: shows the meters installed at the split unit in M1. Right: the plug in meters used for the evaporative coolers

In order to track the electric consumption of the building and ACs, three methods were used. To track the overall building consumption, the occupants' electric purchases were noted every month as the online tracker only held ten transactions (Appendix A.8), and the occupants frequently topped up. For the consumption of evaporative coolers, most were plugged into a socket; therefore, a plug-in meter was used (Figure 3.5). This was impossible in evaporative coolers connected to the main power. Every month the occupants would send photos of the logger's kWh consumption and then reset it for the next month. The plug-in meters also recorded the time of use; however, this was inaccurate in newer evaporative coolers as they constantly consumed small amounts of electricity. For the split units, one energy meter was successfully installed in M1. As this involved an invasive installation by an electrician, the meter was left in situ at the end of the project. Attempts were made to install two more in M1 and T1; however, the split unit in T1 stopped working and was disused. In M1, travel restrictions prevented the electrician from coming to install the second meter.

The data loggers were checked by the occupants each month to ensure the battery is working and that they are logging AC use and occupancy. The data set was checked for inconsistencies every month, at the end of each season and at the end of the monitoring period. Any discrepancies were flagged with the occupants to see if they changed their behaviour. For example, a long period of no AC use could be the logger failing or the occupant stopped using the space for some reason, asking the occupant within the same month helped verify this.. A good understanding of how the loggers work helped find these inconsistencies. For example, the motor loggers could give a false negative if they miss a vibration but they do not give false positives. Understanding this meant that the AC use logged is the minimum likely use and it is possible that the use was higher. Using different types of loggers in the same space and cross checking the different data sets was also very useful in checking the information and its validity. For example, an increase in AC use hours (logged by the motor logger) was reflected by the increase in electric consumption by the plug meter installed on the same AC. Any part of the data that was deemed as unreliable was disregarded to maintain the data set’s integrity. The specific instances are highlighted within the case study monitoring chapters 7 and 8. These challenges highlight the need for robustness when working with developing countries to ensure that data is valid.

The pilot study's results helped identify how many data loggers were needed and what types. The respondents were given logs to record their space use for a sampled weekday and sampled weekend (Appendix A.4). This helped identify which rooms were used the most frequently and when. The loggers logged every 15 minutes from 1/2/2021-1/2/2022. Table 3.3 shows which type of loggers was used in which spaces. The details and specifications of the loggers used is shown in Table 3.4.

Table 3.3 Location and type of loggers used in the case study

House	Space	Thermal	AC motor	AC state	CO2	PIR	kWh
T1	**SE.BD**	Y	Y	Y			Y
	ME.BD	Y	Y				Y
	NC.L	Y	Y			Y	Y
	SW.BD						Y
	SC.BD	Y			Y		
T2	**NE.BD**	Y	Y		Y		Y
	SW.L	Y	Y			Y	Y
	SW.BD	Y					
	NC.BD	Y					
M1	**1.NC.BD**	Y		Y			
	1. NW.BD	Y		Y			Y
	1.NC.L	Y				Y	
	1.SE.BD	Y					
	External	Y					
M2	**NW.BD**	Y	Y		y		Y
	NC.BD	Y	Y				Y
	SE.BD	Y	Y				Y
	SW.L	Y	Y				Y
	SC.L	Y			Y	Y	
Total		18	9	3	4	4	12

Table 3.4 Data logger specifications

Name		Specifications
UX100-003 HOBO Temperature/ Relative Humidity 3.5% Data Logger	**Temperature**	**Range:** -20° to 70°C (-4° to 158°F) **Accuracy:** ±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F) **Resolution:** 0.024°C at 25°C (0.04°F at 77°F) **Range:** 15% to 95% (non-condensing)
	Humidity	**Accuracy:** ±3.5% from 25% to 85% including hysteresis at 25°C (77°F); below 25% and above 85% ±5% typical **Resolution:** 0.07% at 25°C (77°F) and 30% RH
UX90-001 HOBO State Data Logger		**Resolution:** Pulse: 1 pulse, Runtime: 1 second, State and Event: 1 State or Event **Logging rate:** 1 second to 18 hours, 12 minutes, 15 seconds **Time accuracy:** ±1 minute per month at 25°C (77°F) (see Plot A
HOBO Motor On/Off Data Logger		**Resolution:** 1 pulse, 1 second, or 1 State or Event **Time accuracy:** ±1 minute per month at 25°C (77°F) (see Plot A)
UX90-005x/-006x HOBO Occupancy/ Light Data Logger		**Detection Range**: maximum 12 m (39.4 ft) **Detection Performance** 102° (±51°) Horizontal; 92° (±46°) Vertical **Detection Zones** 92
TGU-4500 Tinytag Ultra 2 Indoor temperature and relative humidity data logger	**Temperature**	**Reading Range** -25°C to +85°C (-13°F to +185°F) **Response Time** 20 mins to 90% FSD in moving air **Reading Resolution** 0.01°C or better
	Humidity	**Reading Range** 0% to 95% RH **Accuracy** ±3.0% RH at 25°C / 77°F **Reading Resolution** Better than 0.3% RH
TGE-0011 Tinytag CO2 Carbon dioxide data logger		**Response Time** 110s (typical) **Temperature Dependence** ± (1 + CO2 concentration [ppm] / 1000) ppm/°C (-20 to 45°C/-4 to 113° F) - typical **Reading Resolution** 0.1ppm < ± (50ppm +2% of measured value)

Chapter 4 Unsustainable development in Khartoum

4.1. Overview

"Sustainable development is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" –World Commission on Environment and Development, 1987

Osman and Merghani's seminal studies on the Sudanese courtyard house ended in the early 2000s, just at the start of the oil boom in Sudan. Therefore, research is needed to understand how this socioeconomic change impacted the current lifestyle, building form and prominence of different housing typologies. The government neglected agriculture and industrialisation in favour of a resource that would deplete with South Sudan's separation in 2011. Up until 2011 this situation created the perfect climate for unsustainable development: Economic development fuelled a highly consumptive new middle class in a rapidly expanding city, followed by a deep recession. African cities like Khartoum do not have the finances and government capacity to sustain the current urban demands (Sarzin & Mehta, 2011).

This chapter aims to explore how unsustainable development unfolded in Sudan resulting in an energy consumption rate that is higher than the country's capacity. It explains how urbanisation and irregular economic development patterns cause unsustainable development. A literature review will then map the rapid urbanisation in Khartoum, and the consequential urban sprawl, interviews with experts will follow this to reflect on its impact on housing trends. The economic development patterns in Sudan will then be elaborated on with a focus on the middle class and their consumption habits regarding appliances. The attention will then move to ACs in particular. As information is scarce, interviews will be used to track the AC's history in Sudan. This information in this chapter sets the background needed to understand the pressures impacting current houses in Sudan and will be referenced throughout the thesis.

4.2.Critical drivers of unsustainable development in developing countries

Sudan is classified as a Least Developed Country 'LDC' (UNCTAD, 2018). Almost half of LDC countries' population live in extreme poverty due to unemployment and underemployment, which is further complicated because they also have the world's fastest population growth. On the other hand, the capital and technological accumulation rates are usually slow. These factors, combined with low levels of education and poor infrastructure, hinder the chances of sustainable development (UNCTAD, 2018). As the population grows, people in rural areas migrate to urban centres and shift their work from agriculture to small manufacturing services. This movement from a rural setting to an urban one is called urbanisation. Sustainable development occurs when urbanisation is part of industrialisation and economic improvement, but in a developing country, it happens because the country has transitioned from agriculture to an informal service economy (Cobbinah et al., 2015)

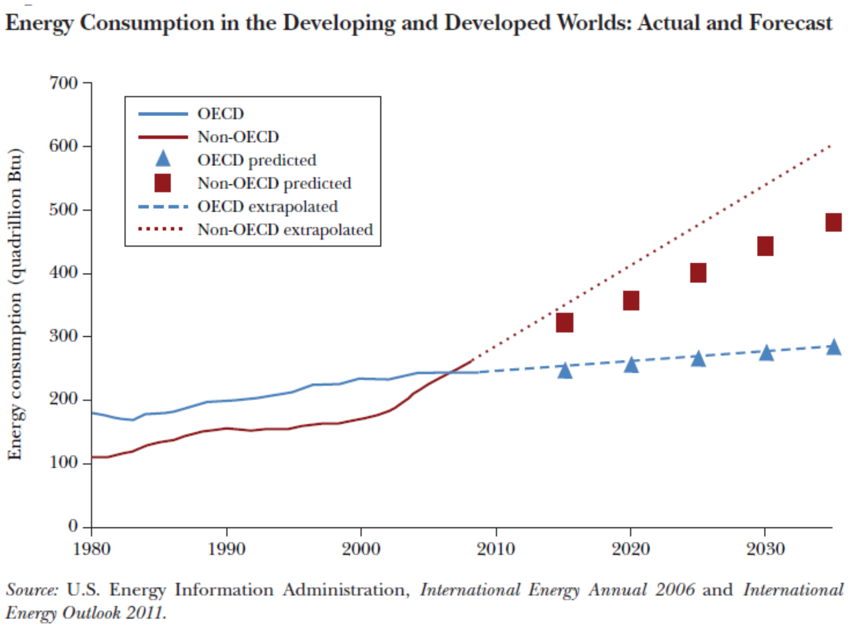


Figure 4.1 The energy consumption in developed countries vs developing countries. Source: (Wolfram et al., 2012)

Though energy consumption in developed countries currently exceeds those in developing countries, this is estimated to change as the bulk of the energy demand and consumption per capita in the next 20 years will come from developing countries. As shown in Figure 4.1 by 2035, developing world demand will almost double developed world demand. Developing countries are now experiencing an increased per capita income (Guarín and Knorringa, 2014). This increase has expanded the middle class in these countries, especially India and China (Guarín and Knorringa, 2014). The middle class in Khartoum has significantly increased after the oil boom. (Copnall, 2014). Economic development increases consumption in developing countries but decreases it in developed countries because of access to new technologies (Mahalik et al., 2017; Sadorsky, 2010). This increase happens because increased GDP per capita in developing countries expands the middle class, increasing appliance ownership and consumption (McNeil & Letschert, 2005).

The expansion of the middle class creates a new middle class who were recently poor, in addition to the existing old middle class. The new middle class has similar consumption habits to the poorer classes, but their consumption grows faster than the old middle classes (Guarín & Knorringa, 2014). This consumption includes energy use as it grows more quickly for households coming out of poverty than for households further up the income distribution (Wolfram et al., 2012). The expansion of the middle class has economic implications such as increased discretionary income, purchasing power, and sociocultural effects with the change of beliefs and traditions (Guarín & Knorringa, 2014).

Increased income increases expectations as people want more than just food and clothes (Hubacek et al., 2007). The energy supply problem in developing countries can be described as a crisis of rising expectations (Rogers, 1991). Emerging economies start discretionary consumption at lower income levels than developed countries (Hubacek et al., 2007). This results in a larger income bracket in these countries behaving as a middle class compared to developed countries with a similar pay increase (Guarín & Knorringa, 2014). In developing countries, for example, a slight increase in income can facilitate the purchase of a car (Sathaye & Meyers, 1985), which leads to significant growth in fuel consumption as the occupants become significantly reliant on the car for transport. The level of urbanisation also impacts the likelihood of a higher wage leading to increased consumption. For example, urban dwellers prioritise cars more than rural citizens who experience the same increase in income (Wang, 2014). Another example is that residents in major cities live more modern lifestyles and consume more than provincial ones (Sathaye and Meyers, 1985).

4.3. Urbanisation

This section aims to understand the current urban conditions in Khartoum. It will first look at the extent of urban sprawl and then at how the population is distributed within the city's boundaries. Then it will explore the city's morphology to understand the distribution of current housing typologies. Finally, it will look at land prices and their impact in driving towards densification.

Population increase and urban sprawl in Khartoum

Though housing has declined in developing countries, the area per person is increasing (Hubacek et al., 2007). This increased area per person caused cities to grow at a faster rate than the population growth (Hubacek et al., 2007; Sathaye & Meyers, 1985). From 1956 to 2006, the size of Khartoum increased by 78 times, despite the population increasing by just 28.5 times (Sarzin & Mehta, 2011). As a result, the density decreased from 22,667 people per km^2 in 1970 to 6,013 in 1980 (Sarzin & Mehta, 2011). Urban sprawl increases pressure on services and resources such as water and fossil fuels (Cobbinah et al., 2015) and causes increased air and water pollution and loss of agricultural lands and natural habitats. (Leichenko & Solecki, 2005). To curb it, the government started to make plot sizes smaller (Hamid & Elhassan, 2014). Plots for sites and services were reduced to 250-350 m^2, and the size of re-planned squatter areas to 100 m^2 (Murillo, 2008). The three formal classes were each halved, a first-class plot became 400 m^2, a second class was 300 m^2, and a third class was 200 m^2 (Sarzin and Mehta, 2011).

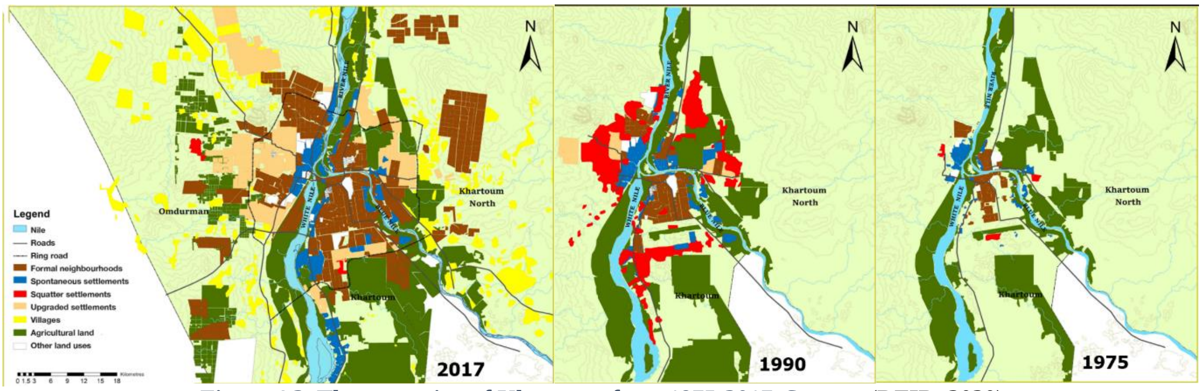


Figure 4.2 The expansion of Khartoum from 1975-2017. Source: (DFID, 2020)

Figure 4.2 shows how this expansion occurred geographically (DFID, 2020). In 1985, internally displaced people (IDP's) constituted 50% of the city's population, and 67% of Khartoum was informal settlements (as shown in 1990) (Sarzin & Mehta, 2011). These squatter settlements created a belt around the city called the prerogative term 'the black belt' (seen in red in 1990) (Pantuliano et al., 2011). Urbanisation driven by conflict-induced displacement significantly strains the city as these immigrants usually come without resources (Sarzin & Mehta, 2011). From 1990 till 2017, the government worked on upgrading these settlements and integrating nearby villages while also expanding formal neighbourhoods. Only 8.6% of the city remained informal settlements by 2011 (Sarzin & Mehta, 2011).

Irregular density distribution in Khartoum

60% of the current housing stock in Khartoum is in poor condition (Murillo, 2008). The urban poor lives in 177 km^2 out of the 1,323 km^2 of Greater Khartoum. They constitute 60% of the population yet only occupy 13% of the city. This explains why their densities reach 583 person/hectare compared to the city's average density of just 42 person/hectare (Murillo, 2008). The remaining 40% of the population lives in the middle- and upper-class neighbourhoods (Mcgranahan et al., 2020).

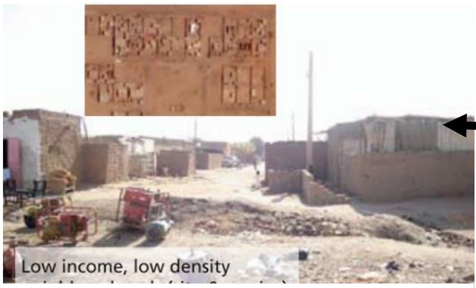


Figure 4.3 A sites and service area, low density low income area. Source: (Murillo,2008)

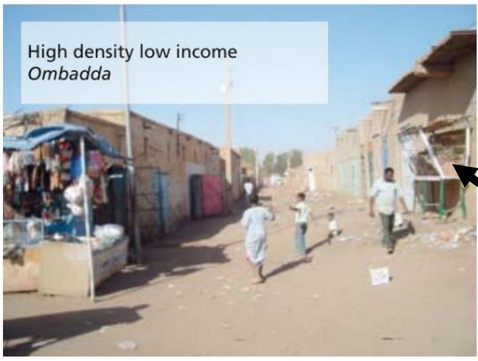


Figure 4.4 Ombadda, a High density low income area. Source: (Murillo,2008)

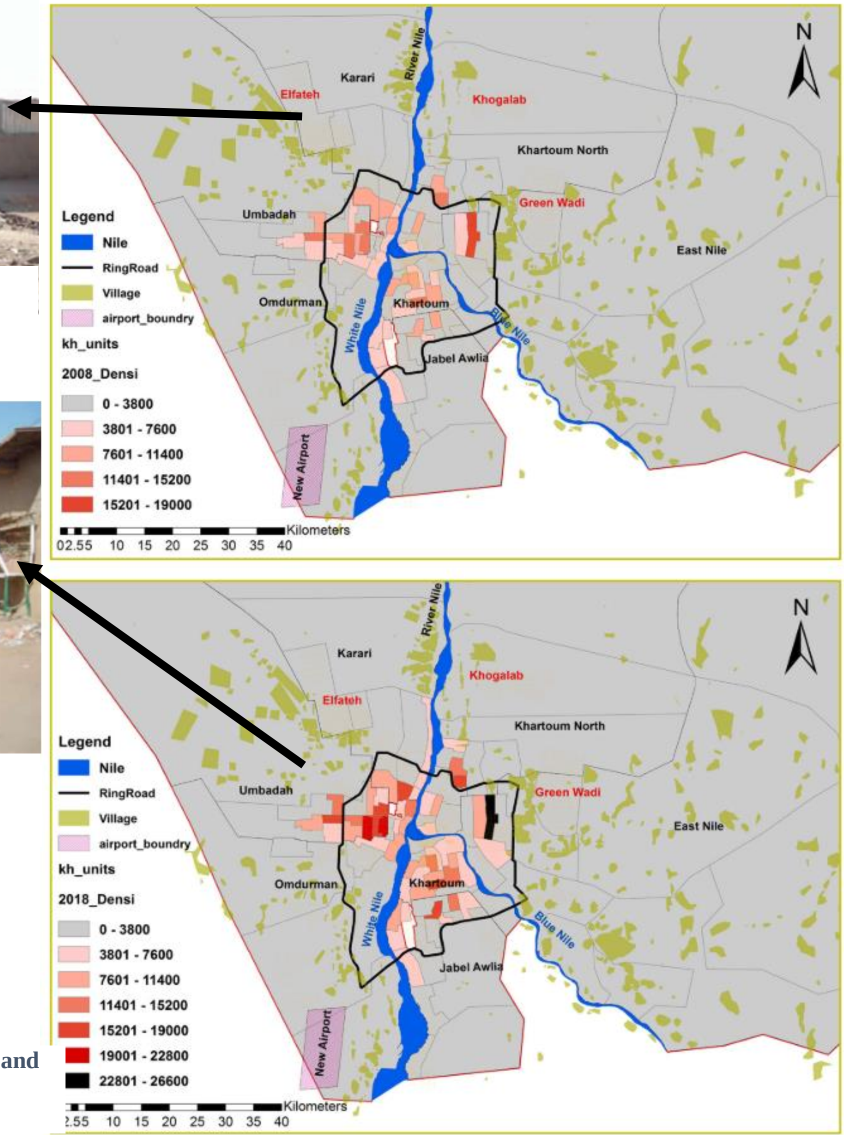


Figure 4.5 A comparison between 2008 and 2018 in terms of density. Source: (Murillo,2008)

The report by the Institute of Development Studies (IDS) attempted to map the density increase after 2008 when the last census was made (Mcgranahan et al., 2020). The map in Figure 4.5 shows a general increase in density within the ring road and outside it in Omdurman and Khartoum north. However, the highly dense areas in Khartoum are due to multi-story housing (Figure 4.6) of the middle classes. At the same time, in Khartoum north and Omdurman, it is due to overpopulated single-story houses such as Ombadda, a high-density low-income area (Figure 4.4).

Figure 4.6 A middle income area in Khartoum, Alsahafa. Source: (Ibrahim & Omer, 2014)

The morphology of Khartoum and Omdurman

Greater Khartoum is not morphologically uniform; therefore is essential to understand the distribution of these different topologies. A survey in 1998 revealed that 89.5% of all houses in Khartoum were ground-floor courtyard buildings, which was reduced to 75% within 3 years (Merghani, 2004; Eltayeb, 2003). In 2008, only 6.3% lived in flats and 0.3% in villas. (Pantuliano et al., 2011), However, many neighbourhoods in Khartoum are undergoing a wave of gentrification from expats (Pantuliano et al., 2011), which means these figures have most likely changed. As this chapter will later discuss, many expats have returned to Sudan since 2017, which means an increase in multi-story housing.

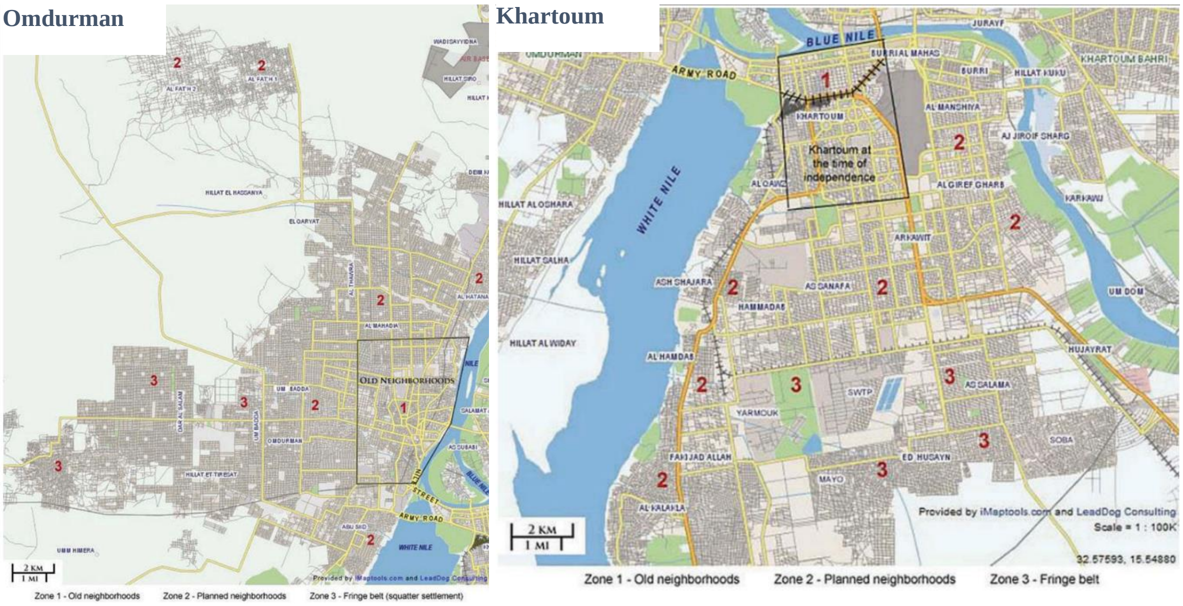


Figure 4.7 The morphology of Khartoum and Omdurman. Source (Ibrahim & Omer, 2014)

Figure 4.7 shows the three zones that constitute Omdurman and Khartoum. Zone one is the core, zone two is the planned neighbourhood, and zone 3 is the fringe belt. In Omdurman, up until the 1980s, most houses were made using mud. In the 1970s, only 5% of roofs were concrete or corrugated iron rather than the prevalent mud and straw (Ahmed, 1978). By the 1990s, instead of preserving these buildings as heritage, most of them had been demolished and replaced by red bricks and cement (Ibrahim & Omer, 2014). A similar practice happened at the New Diems in Khartoum (Ahmed, 1978). A change of materials does not necessitate a change in form, especially when that form fulfils other needs. In zone 1, buildings in the streets leading to the central business district (CBD) are up to 5 stories high, while the neighbourhoods behind them are usually one-story buildings with few scattered multi-story buildings. Zone 2 constitutes poorly serviced new planned areas that were once agricultural land. Zone 3, the fringe belt, is made of squatter settlements that are now upgraded (Ibrahim & Omer, 2014).

The core is void of residential areas in Khartoum, and the CBD is mainly multi-storey. Up until the 1960s, most houses on the core were single-story. Zone 2, like Omdurman, is also made up of planned neighbourhoods that were previously agricultural lands and are dominated by one-story buildings in third-class areas. However, First and second-class areas in Khartoum are mainly 3-4 story villas owned by expats who returned from the gulf in the past 20-30 years. Khartoum's fringe belt has a sewage plant, a planned neighbourhood, a military complex, a squatter settlement and a green belt (now removed). (Ibrahim & Omer, 2014)

Land price increases

Land prices have soared in the past years in Sudan because land is seen as a commodity, given the high inflation rates (DFID, 2020). From the early 1990s, the government further exacerbated this problem by selling land as an income source (Sarzin & Mehta, 2011) and charging high fees for turning agricultural land into residential (DFID, 2020). Figure 4.8 shows that central areas were up to 5 times as expensive as peripheral areas in 2008. It also shows that land in Khartoum is more expensive than in Khartoum North and Omdurman, which could explain why more high-rise buildings are present there.

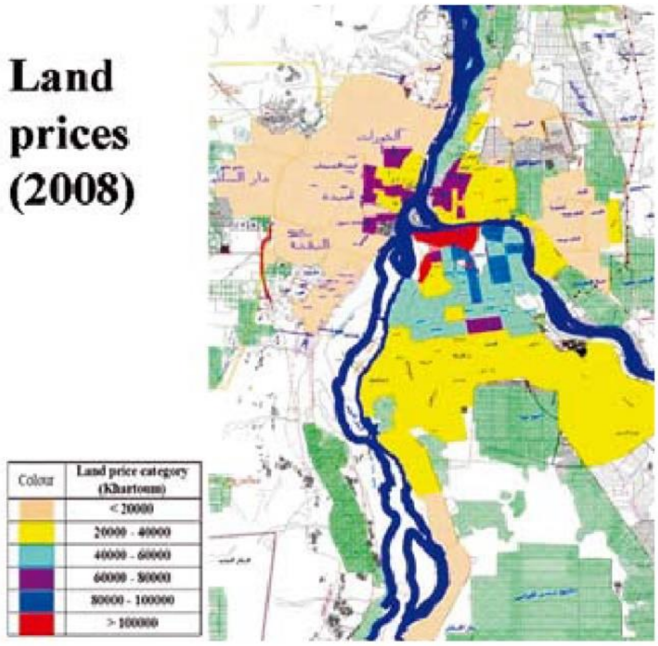


Figure 4.8 Land prices in Khartoum in 2008. Source: (Murillo, 2008)

A study in 2003 found that 91% of Khartoum residents would prefer a detached house to an apartment (Mohammed & Kurosawa, 2005). While another in 2006 found that 78.2% of residents in Khartoum preferred their current setting to a compact one (an apartment) (Elghazali, 2006). In the past, flats were unpopular because of their lack of privacy, family sizes, poor sewage services and how unsuitable they were to the climate (Ibrahim & Omer, 2014) (Awad, 2019). Despite their perceived drawbacks, they are becoming more common.

4.4. Urbanisation in light of poor government building regulations

Building regulations in Sudan are outdated, improperly applied, and not followed up by construction-as-approved checks (Ramadan & Feng, 2004). The rapid urbanisation has created an annual demand of 60,000 new housing units per year (Murillo, 2008).This high rate pressures the government's capacity to control and monitor the construction of new buildings; thus, only 7.5% of new buildings are issued with permits (Murillo, 2008). This problem is not recent; a study in 1978 concluded that this lack of monitoring allows homeowners to haphazardly expand within their plots to allow for subletting (Ahmed, 1978). A series of interviews were conducted with architects and civil servants to understand the impact of increased densification given poor building regulations. They also assessed if it was practical to include this study's framework in a sustainability code. Table 4.1 shows the interviewees.

Table 4.1 Interview guide

Interview	Interviewee	Title/ Workplace
AC expert 1	AC industry expert with academic background	Division head at an AC distributor 1
AC expert 2	Mechanical engineering lecturer	University of Khartoum
AC expert 3	Architect specialising in passive design and mechanical ventilation	Sudan university of science
AC expert 4	AC industry expert with seven years in Sudan and experience in the Arab gulf	Division head at an AC distributor 2
AC expert 5	AC industry expert	An employee at an AC distributor 3
Civil servant 1	Architect and civil servant	Head of division at a ministry of planning in Khartoum north
Civil servant 2	Architect and civil servant	Head of division at a ministry of planning in Khartoum
Civil servant 3	Architect, civil servant and academic	Committee member of the sustainable building code
Architect 1	Architect	Employee at an architectural office
Architect 2	Architect	Freelancer

Construction trends in Sudan and their impact on law breaches

Multi-story buildings in Sudan are increasing, especially in expensive lands where people want to build more floors to cover costs. This pressures architects to break building code to achieve maximum return on investment. Civil servant 1 said, *'Some people even calculate how much money they would have to pay for a fine compared to the financial gain of an extra illegal floor'.*

The pressure manifests in two ways, either the client wants as much coverage as possible or wants to add illegal commercial spaces such as shops or studios instead of apartments. During the interview, all the architects and civil servants had reservations about several laws. The architects stated that if the client's requirements clash with regulations, they inform them of this but immediately offer to submit a planning process design and a different actual design. *"They -the clients- know this is illegal, we tell them that this will not pass the building permit, but we also tell them that they can bypass this by submitting two different sets, and they agree to that."* Architect 1

They do this because they do not believe these laws are relevant or logical. The architect has complained that the laws are rigid and should allow for case-by-case reviews where the specific project context is included in the planning decision. The three civil servants' responses to these 'irrelevant' laws varied from ignoring breaches of those laws to actively trying to change the law. Civil servant 1, on the other hand, argues that architects break the law when their poor design skills hinder them from finding reasonable solutions. For example, to add more spaces, they would frequently create spaces with no windows and try to validate this breach by saying that split units do not require outdoor ventilation like evaporative coolers. Client's pursuit of maximum return on investment could pressure the architects who must balance these demands with what they view as 'rigid laws'.

During the design phase, the architects mentioned that breaches on the building interior, such as rooms smaller than standard, could be passed if the applier had an inside contact in the ministry. However, outer breaches such as setbacks will not, so they submit a fake set to the ministry to cover them. Architect 2 added that knowing a high-ranking figure inside has allowed her client to pass a significant breach, but this is rare.

This emphasises that even if they are going to break the law, civil servants focus on specific laws and aspects over others. This concept carries on to the construction monitoring phase as well. Four interviewees said changes to partitions, doors and windows are not monitored during construction. The fieldwork crews only focus on conforming to structural details like column sizes and setbacks. This is problematic as changes in window placement affect ventilation, as mentioned by civil servant 1, and changing the apartment sizes increases user density, as mentioned by civil servant 2. This unregulated density increase pressures on the building's services, such as sewage, water, electricity, and ventilation, as buildings exceed their officially designed capacity.

Enforcement is weak in Sudan because the ministry has limited resources. For example, Sharq Elnil district has 2 million people, is 7,867 square kilometres large, and only has two field cars to monitor its construction sites, according to civil servant 1. The high inflation rates reduced salaries' value, leading to reduced motivation and higher chances of bribery. The lack of funds also reduced much-needed training, according to civil servants 1 and 2. Civil servant 1 said the ministry could not assess detailed design documents showing crucial details like shading devices and material types. These details are fundamental in assessing the environmental performance of the building. It will be challenging to introduce sustainable laws if the ministry focuses on setbacks and structural details while neglecting internal building details.

Mandatory sustainability policies compared to voluntary sustainability codes

In 2016, a committee formed by the Ministry of Planning was tasked with creating a sustainability code for Khartoum. It is comprised of two ministry representatives and four university professors. However, work was halted due to political instability. Four interviewees believed it was doubtful that a sustainable code could be realistically enforced but should be voluntary, while architect 2 disagreed and thought it should be a flexible law. Architect 1 and civil servant 2 said homeowners are unlikely to adopt practices that clash with their investments. This further emphasises that investment return is the main driver for law breaches. This has many implications for sustainable designs. For example, a large balcony or veranda will most likely be closed off to add additional floor space as the family expands, which has happened in three case studies, as will be explained in Chapters 5 and 6.

The architect must convince the homeowner of a benefit more significant than the additional space. Another example would be outdoor spaces that consume money to construct and maintain. The architect must justify how the additional green space can be worth it through reduced cooling or increased productivity. Architect 1 mentioned that only clients who request gardens are wealthy villa owners. Monetary incentives by the government are also necessary, according to Civil servant 2. Civil servant 3 stated that the main challenge faced by the committee was awareness and the lack of communal thinking among Sudanese architects; each architect is concerned with only meeting their client's requirements. Viewing sustainability as a necessity and shared responsibility are both essential for adopting sustainability in developing countries (Reffat, 2004).

In conclusion, the current climate does not allow any sustainable code to be implemented. Especially with the ministry's focus on structural elements only. Proposed solutions need to be justifiable with a clear return on investment due to the increasing pressure of densification.

4.4.The middle class and their consumption habits

This section aims to quantify the size of the middle class in Sudan and its impact. It starts by defining what constitutes the middle class and then tracks the evolution of the middle class in Sudan. It then focuses on their general consumption patterns regarding appliances, particularly the AC.

Measuring wealth and defining the middle class

It is hard to define the middle class as it depends on the socioeconomic perspective and geographical context. A middle-class Western family, for example, would likely be considered upper class in a developing country. Sahal studied the Sudanese middle class and described it as salaried middle-level and junior employees, petty merchants, tenant and peasant farmers, and pastoralists who depended on employed labour to carry out their activities (Sahal, 1999). However, even senior employees and professionals are sometimes middle class, not upper, due to poor economic conditions in Sudan. He considered that the absolute poverty line for Sudan was $27 per month per person in 1996.

The International Wealth Index (IWI) (Smits, 2013) gives a scale of 0-100 to houses based on the state of the house and the number of appliances owned. Figure 4.9 shows the appliances required for each level. It was created based on the MICS and DHS reports. The value 50 correlates with a Poverty Headcount Ratios of $2.00 per day, while 70 is considered a poor household. Therefore, for our context, we shall consider houses above 70 as middle-class. The global data lab which produced the IWI states that Khartoum had an average IWI of 61.5 in 2014, with 59.1% of houses below 70; this correlates with the statistic that 60% of housing is in poor condition (Murillo, 2008). As a rough estimate, the remaining 40.9% are either middle or upper classes. This figure is an increase compared to 1975 when only 10% were middle class, 5% were upper class, and the remaining 85% were lower class (Ahmed, 1978).

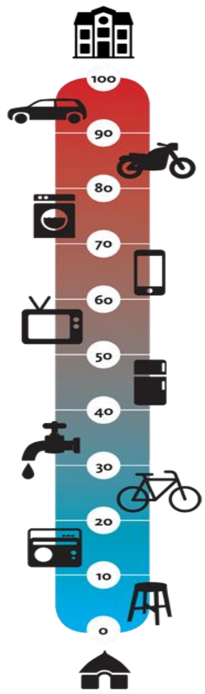


Figure 4.9 IWI ladder. Source: (Smits, 2013)

The evolution of the middle class in Sudan

As mentioned in section 4.2, the middle class has two consumption patterns based on whether it is the old or new middle class. Until the 1980s, Sudan had a middle class composed of professionals from all sectors who had a thriving social community with clubs dedicated to each profession (Baldo, 2015). This class was a legacy of the British colonial government (Deshayes, 2019). A large portion of this middle class were foreigners who also each had their national clubs (Greeks, Coptics, Jews etc.) (Abboudi, 2019). Then Sudan adopted the IMF recommendations, which caused an economic crisis that increased the number of poor houses from 1.6 million in 1978 to 2.6 million in 1986 (Sahal, 1999). This means that 1 million houses were no longer middle class. The economic crisis meant that the Sudanese "effendiya" or government employees were no longer the standard middle class as only 6% were above poverty by 1996, and 77% of the middle class suffered a budget deficit by 1989 (Sahal, 1999). Many of these professionals left Sudan to pursue better opportunities abroad (Baldo, 2015). This vacuum was filled by the military regime established in 1989. The regime created a new political elite loyal to it and monopolised resources to cement its rule (Guibert, 2016). As they gained power, the classes were reduced to just two: the ultra-rich and the poor (Sahal, 1999).

This class distinction is evident in the urban landscape of Khartoum's juxtaposition of a few affluent neighbourhoods surrounded by large swatches of low-income areas, as mentioned in section 4.3.

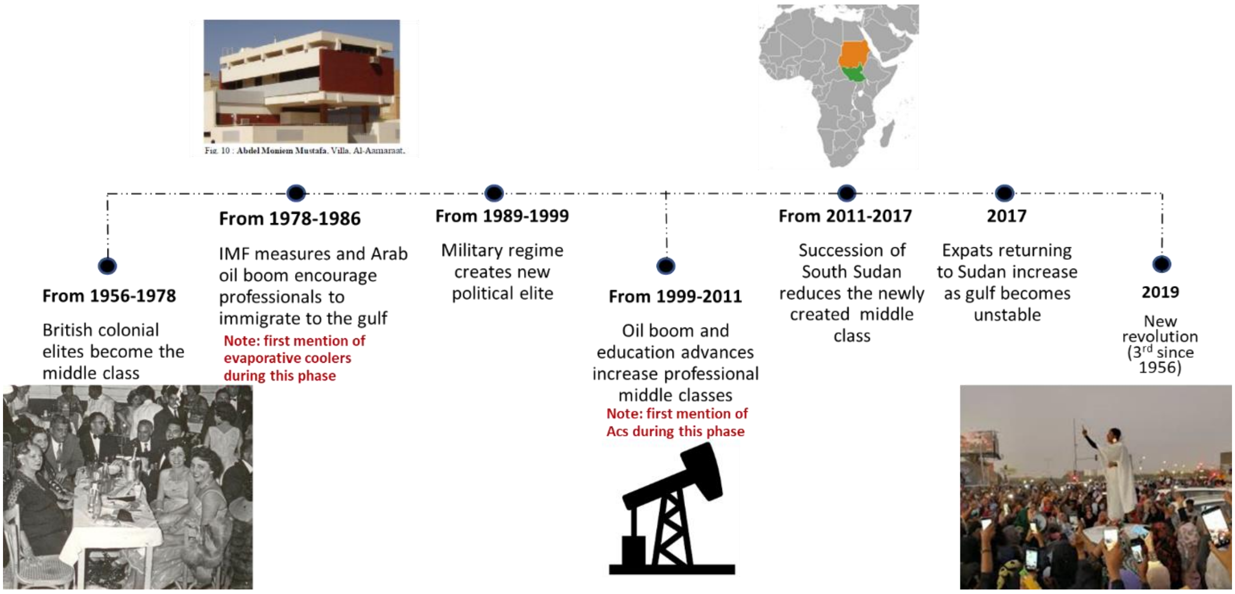


Figure 4.10 The history of the middle class in Sudan, illustrated by the Author

Between 1999-2011, the regime created an educated middle class to reshape society into an Islamic mould. This class later rebelled against it in 2019 (Deshayes et al., 2019) because, as mentioned in section 4.2, an increase in income causes an increase in expectations. This new professional class was heavily influenced by social media and aspired to a modern lifestyle (Deshayes, 2019). However, after the boom, the growth was short-lived as high inflation rates meant employees with fixed salaries lost income value compared to people with flexible income sources, such as merchants (Deshayes, 2019). The high inflation rates meant only two groups could keep their status as the middle class. The first group benefited from the regime, which survived through corruption. The second group was those receiving remittances from relatives abroad (Baldo, These classes have high consumption rates and explain the 2 billion dollars spent annually on imports in an impoverished country (Baldo, 2015). Inflation rates increase with the black-market dollar rates. Because they receive the remittances in dollars, it could be speculated that they are significantly less impacted than those with Sudanese pounds as their income source.

Impact of Sudanese expats

Since expats created a "nouveau riche" class through their remittances, this section will focus on their impact in general. Expats are a major source of hard currency for Sudan after the succession of South Sudan in 2011 (*Sudan Tribune*, 2013). RT news estimates they send 4-5 million dollars annually (Aga, 2017). Most concrete buildings in peripheral areas of Khartoum are built by expats or people who sold lands they inherited in the centre and used the price difference to build on the peripherals (Eltayeb, 2003). Ever since the 1970s (the Arab oil boom), returning expats have been bringing to Sudan the modern ideals and consumption patterns of the gulf (Bashier, 2007). This includes the introduction of the Mediterranean villa.

Saudi Arabia (KSA) has the largest population of Sudanese expats (GLMM, 2018). Although official figures from the Gulf Labour Markets, Migration, and Population (GLMM) Programme in 2013 put them at 500,000, al-Khartoum daily news reported that there were 900,000 immigrants during that year(*Sudan Tribune*, 2013). RT news even puts them at 3 million (Aga, 2017).

47,000 Sudanese expats were deported in 2017 as part of KSA's "Nation without Violator" program to reduce illegal immigrants (Aga, 2017). Between 2017-2018, 900,000 expats (from different nationalities) left Saudi Arabia after it introduced new nationalisation policies aimed at reducing the expat population in 2017 (*Gulf Business*, 2018). This resulted in a huge influx of returning expats in Khartoum which has pressured housing due to increased prices and services such as electricity and transport in the city.

The middle class and appliance ownership

"Convenience is a major motivating force in the transition to modern methods. So is the desire for more service: more cooling than ventilation provides, more entertainment than radio provides" (Sathaye and Meyers, 1985, pg.11).

Section 4.2 established a correlation between appliance ownership and middle-class status; therefore, it is necessary to understand the relationship dynamics between them. GDP growth does not directly increase appliance ownership growth, but rather the number of houses entering the middle class because of this GDP growth that drives this increase (McNeil & Letschert, 2005).

Wealthier households increase the quality of their services by increasing the number of appliances, such as having several lights, as opposed to low incomes who only have one or two lights (Sathaye & Meyers, 1985). However, although convenience is the main driver behind each appliance individually, these appliances are advertised collectively as a necessity for a modern urban lifestyle (Leichenko & Solecki, 2005). The first appliance a citizen in a developing country buys when the economic means become available is a TV followed by a fridge and then a Fan (Wolfram et al., 2012). This is because their societies are used to buying fresh produce daily, reducing the need for fridges. Increased TV and mobile ownership rates have made it easier for Mass Media to reach more people in developing countries (Leichenko & Solecki, 2005). Mass Media and the spread of western advertising and products spread the adoption of western and modern ideologies (Leichenko & Solecki, 2005). The Arabian Gulf, especially the UAE, is heavily impacted by western ideologies (Hills & Atkins, 2013). Thus, these influences reach Sudanese citizens directly through the media and indirectly through returning expats from the Arabian gulf.

Saudi, Qatari and Kuwaiti companies finance urban projects in Khartoum that mimic their 'hypermodern' model (Choplin & Franck, 2010). Gated private compounds marketed towards these returning expats started emerging in 2003. (Elhadary & Ali, 2017) This is proven by the fact that 70% of their owners are expats, while the remaining 30% are mainly military men (Elhadary & Ali, 2017).

The increase in AC ownership as a global trend

ACs add a significant electric load that even a first-world state like California struggled to accommodate. It requires substantial funds to increase the grid's capacity, leading to power shortages (McNeil & Letschert, 2005). The US consumes more energy for AC use than all other countries combined, which is why it is used as a benchmark for high AC energy use (Sivak, 2013). Appliance ownership is affected by urbanisation, electrification, and cost. Climate is considered an additional factor if the appliance is an AC (mcneil & Letschert, 2005). The countries with the most cooling degree days are also the poorer countries that cannot afford AC (mcneil & Letschert, 2005).

Figure 4.11 The consumption of Sudan if it reaches full saturation. Source: (Sivak, 2013)

Figure 4.11 shows that if Sudan reaches the same saturation as the USA, it will be the 14th largest consumer of electricity due to its large population and a high number of cooling degree days. Sudan has around 3500 cooling degree days (Sivak, 2013). Osman analysed Khartoum's predicted climate change scenario based on data collected from 1981 to 2015 (M. M. Osman & Sevinc, 2019).

In the EU2C scenario, annual comfort, according to the adaptive comfort model in the ASHRAE 55 in Khartoum, is predicted to decrease from 27.1% to 11.7%. Climate change will increase dust storms, which makes it essential to use mechanical ventilation filters. Khartoum is divided into hot, wet and dry seasons. The dry season from November to February is expected to have a drop in RH values, which are already usually low, around 8-10%. The hot season from March to May includes an annual temperature increase by 0.01ºC in addition to the relative humidity decrease. In the wet season, from June to September, the temperature increase is 0.02ºC annually, while humidity will increase by 0.2%. Rainfall will decrease, but extreme flooding will become more common.

In urban China, there were eight air conditioning units for every 100 households in 1995; by 2009, there were 106 units for every 100 (Wolfram et al., 2012). Domestic production increases affordability by reducing import costs (Kunzle, 1980). Wealthier families are less likely to monitor their AC use and will more likely have a larger AC and more units (Kunzle, 1980). This is why electricity consumption by the economically well-off in developing countries differs little from that found in the United States or Europe (US Congress, 1991). Even though elites are already getting wealthier, it is the growth of the middle class that will impact AC increase the most (Kunzle, 1980). This is because, as mentioned previously in 4.2, the new middle class increase their consumption at a higher rate than the old established middle classes. The history and trend of AC use in Sudan are not well documented, so interviews will be needed to understand how trends in Sudan are influenced.

4.5.Air-conditioner use in Sudan

Mixed mode buildings are prevalent in developing hot countries as they cannot afford to install Air conditioning in all the spaces (Honnekeri et al., 2014). This section tracks the history and demand of ACs in Sudan through interviews and tracking annual import reports from 1977-2018.

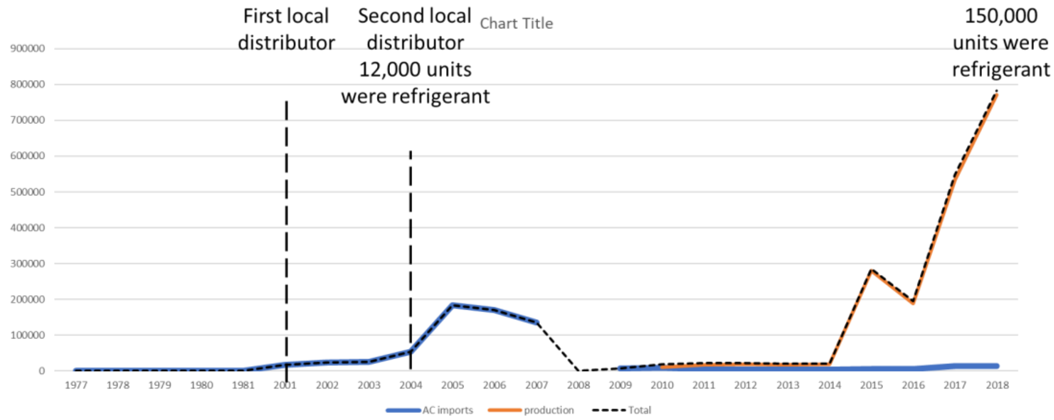


Figure 4.12 AC imports and production levels in Sudan (Source: various annual reports from Sudan bank)

The National Statistics show that in 2008, 55% of Khartoum residents had just a fan, 24% had neither a fan nor an AC, and only 21% had AC coolers. Figure 4.12 shows that the total number of units imported to Sudan from 2003-2008 was around 630,000. Between 2013 and 2018, 1,900,000 units were imported, which is three times as much. This means the actual percentage of AC owners in Khartoum is probably higher. These figures include evaporative coolers and refrigerant ACs.

Figure 4.13 To the left: A split unit with the indoor unit above and the outdoor unit below. In the middle: an evaporative cooler. To the right: A window unit. Source: Digitech (LG Sudan) website

A sample of AC units available at a major AC company in Khartoum is in Figure 4.13. There are three major AC types for residential buildings in Khartoum: Split units, evaporative coolers, and window units. Evaporative coolers push air through wet straw to increase the humidity of the air and allow the water droplets to absorb excess heat(Ministry of Energy, 2015). Split units and window units are refrigerant-based. The difference between window units and split units is that in window units, the heat exchangers, compressors, motors and connecting pipes are placed on the same base, which is why they require an external wall to expel the hot air outside. Split units put the cooling part inside (called the indoor unit) and the hot part outside (outdoor unit), and they also constantly turn on and off to reduce consumption (Ministry of Energy, 2015). Table 4.2 shows that split units consume more than Evaporative coolers and window units of the same strength. However, because split units do not work constantly, they spend less during use. Split units are also the most expensive, as shown in Table 4.2.

Table 4.2 Details of different AC units available in Khartoum. Source: (Digitech records in 2020)

AC type	Strength/ Btu/h	Price in SDG	USD equivalent	Electric consumption/ kWh
Split unit 1	12,000	54,990	687	1.29
Split unit 2	18,000	69,990	875	1.64
Split unit 3	24,000	83,990	1050	2.10
Evaporative cooler 1	8,000	21,990	275	0.18
Evaporative cooler 2	5,000	16,990	212	0.09
Window unit 1	12,000	35,990	449	1.16
Window unit 2	18.000	46,990	587	1.51
Window unit 3	24,000	51,990	649	2.37

Airconditioning history and demand pattern

The author has not found any official records or statistical data on the history of AC adoption in Sudan; therefore, the interviews with 5 AC experts were used to estimate the change in demand for different AC types in Sudan. According to AC expert 2, American Essex locally produced evaporative coolers in the 1960s. An article in the Bureau of International Commerce in 1965 confirms this. AC expert 3 revealed that expats from the Arabian gulf popularised the first evaporative coolers, hence the Sudanese name 'desert AC' for evaporative coolers. He mentioned that it was readily accepted due to two factors:

The similarity of its use to the traditional practice of spraying the yard and the revered position Saudi Arabia has in Sudanese and Islamic culture. Interestingly, according to AC expert 2 and AC expert 3**,** it was also expats who introduced window units in the late 1970s and drove demand for them. This coincides with the Arab oil boom. AC expert 3 said: *"They came -annually- with their luggage, gifts, and air conditioners.*" AC expert 2 stated that wealthy expats built large airconditioned houses, which set the trend and have now become the norm. After that, ACs were no longer considered a luxury but a need, according to AC expert 1. During the late 1990s, split units were sold imported and sold at duty-free markets before the demand allowed more significant imports to be sold at independent shops. In 2001, SEABAL officially started business as the first local distributor of an international brand (General), followed by Digitech in 2004. Digitech performed a study in 2004 that showed that only 12000 refrigerant-based units were imported to Sudan that year. The oil boom in Sudan amplified that demand until 150,000 refrigerant-based units were sold in 2019. AC expert 3 believed that due to this economic prosperity, Sudanese people adopted modernity by buying cars, and installing ceramic tiles, TV receivers and ACs. This aligns with the discussion in section 0, that adopting AC use is part of a wider trend towards modernity. AC expert 4 mentioned that to improve their sales, they conducted an awareness campaign to reduce people's reluctance towards refrigerants. He found that evaporative coolers are more common in outer states than in Khartoum. This could be because, as AC expert 2 said: "*lower classes favour evaporative coolers*", and section 4.4 revealed that outer states are significantly poorer than Khartoum. Due to the current economic recession, AC expert 3 showed that he is seeing a trend towards people returning to their old evaporative coolers to reduce the high electric bill of air conditioners. This shows the impact of unsustainable growth in developing countries. Trends that emerge during times of prosperity are hard to maintain during frequent recessions. All the interviewees believe the future trend will be towards increased AC use due to the harsh climate that will only worsen with climate change and the direction of current social trends. AC expert four also reported increased demand for central units in private villas, which is why they started importing tropical versions

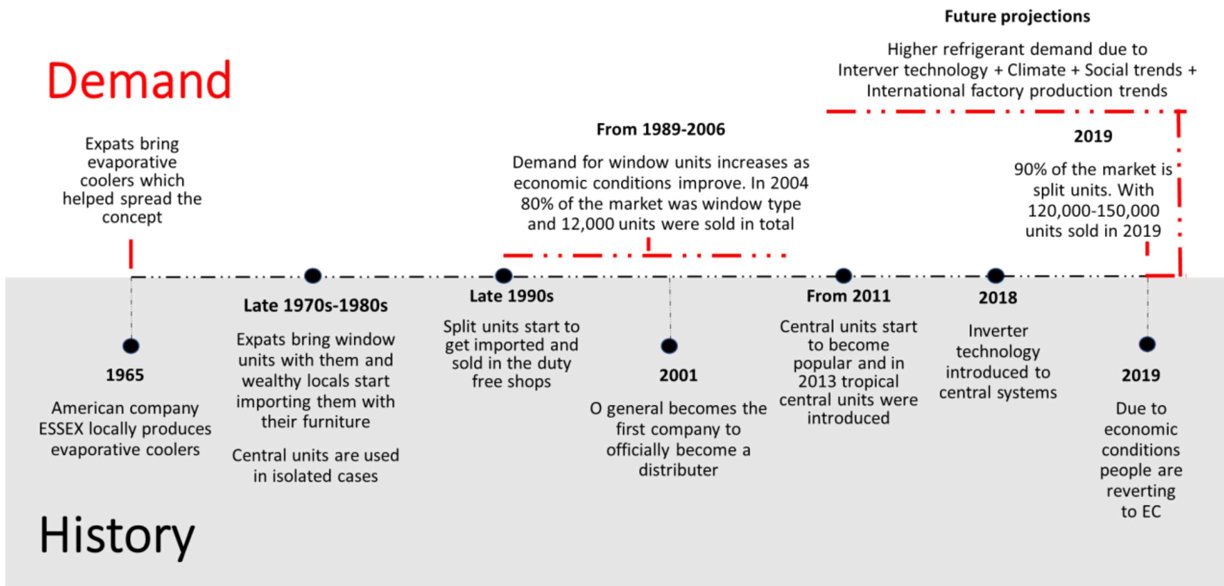


Figure 4.14 The history of AC demand in Sudan, illustrated by the author.

Figure 4.14 summarises the trends and demand for ACs. What stands out is the cycle of expats bringing a new AC type followed by the establishment of mass local production and import, which facilitates locals to buy more. As mentioned in chapter 2, Sudanese people are 'society oriented' (Ahmed, 1978), and highly conformist. Being distinct or different is a taboo (A. Osman, 2014). An interviewee in the case study M1 said, *'in the past, everyone had similar houses, whether you were rich or poor because social conformity and solidarity with your neighbours was more important than showing off'*. This contrasts highly with the flashy 'Dubai-style' culture of the Arabian Gulf. It can be argued that Sudanese expats imported this culture with them when as AC expert two mentioned, '*they built their nice large air-conditioned houses'*. This sets a new bar for what is 'socially acceptable', and local people feel pressured to upgrade their homes to keep up with the trends. This pressure is evident in how the occupant in case study T3 describes how he decided to upgrade his house: *"then ceramic tiles and false ceilings appeared -as a trend- and so we installed them*". In the interview with the case study T1, the occupants said they would not adopt any solution that is considered socially inferior, like having 'mud walls' despite acknowledging its advantages over brick. They also said they want the guest area to be the best conditioned to maintain their social status. To conclude, it can be argued that the appeal of air conditioners in Sudan is driven not only by the thermal comfort it provides but also by the social pressures introduced by expats.

4.6. Conclusion

African cities like Khartoum pose a distinct architectural challenge. The fluctuating economic situation has expanded the electric demand through the modernised middle class, but the supply in terms of the grid is struggling. Urbanisation has put a significant pressure on available resources, including the ability to regulate and govern construction. The expansion of the city is likely to have security implications. Another impact is that the increase in density is likely to change the community cohesion, especially since the expansion is mostly through immigration. The pressure from land price increases leads to overcrowding in poorer areas and a drive towards multi story buildings in richer areas. The city is a mix of a minority of privileged individuals (40%) driving the bulk of consumption and a large swathe of poor households (60%). The recent spike in AC installations could be attributed to the rise in both local production and imports through dedicated suppliers. However, this supply is a response to the increased demand. Individuals have imported ACs since the 1960s; however, the demand was not enough to support the launch of a local distributor until 2001. It could be theorised that the increased demand results from the transition towards modernity and the increasingly indoor lifestyle discussed in Chapter 2. Traditional buildings are not designed for prolonged use, and ACs would be needed to cover the extended hours. The following chapters will test this theory by exploring when the AC was introduced into the case study buildings in relation to the other changes in the building.

Chapter 5 The modified traditional house, a futile response to Modernism

5.1.Introduction

It was established how the Sudanese house, through different typologies, historically adapted to socioeconomic change in chapter 2, which was followed by chapter 3, identifying the recent socioeconomic developments and their impact on AC use,. This chapter aims to build on both chapters by tracking how the courtyard house changed at the individual house level under the current pressures. This will include looking at how the interaction between the building, occupant and AC gradually changed over time. This will help identify the drivers for change that will need to be considered in any future solutions. The chapter's parameters and methodology will be further explored in this introduction. Then each of the three case studies will be analysed by describing the neighbourhood and the family's previous life, followed by an overview of the house's evolution before detailing the specifics over three or four phases. Finally the chapter's conclusion will reflect on the common trends.

Traditional buildings tend to be responsive to slow cultural changes (Estaji, 2018), and their adaptability has been key to their survival, especially in urban contexts (Kotharkar & Deshpande, 2012). These changes were typically in response to internal forces such as the current political climate, local supply chains etc., which limited their scope. However, modernization has sped up this process (Kotharkar & Deshpande, 2012), while globalization increased the number of possible drivers like mass media and consumerism. On the local level, the recent economic boom and subsequent recession mentioned in section 4.3.2 can be considered strong catalysts. Vernacular buildings that do not cope are abandoned or modified '*to reflect the peoples' changing.'* (Gabril, 2014, pg.57).

The previous studies tracking the relationship between Sudanese houses and their occupants were conducted in the early 2000s, which creates a need to establish a new 'setpoint' documenting the current conditions given the faster rate change over the last 20 years. The overarching objective of mapping transformations in the built environment is to understand the underlying causes and predict future patterns. The study of these transformations requires a multi-disciplinary and holistic approach (Estaji, 2018), which alongside studying changes to the physical structure of the building, also investigates the underlying socioeconomic drivers of these changes (Kotharkar & Deshpande, 2012). This is because cultural aspects have shaped traditional building forms, even more than climate (Markus, 2016), especially in the context of the middle east and Africa (Al-mohannadi & Furlan, 2022). Understanding these socio-cultural nuances allows architects to incorporate the essence of traditional architecture into modern buildings (Paul & Modi, 2014). Several studies have also emphasised that the occupant must be considered part of the building (Agorsah, 1986; Estaji, 2018). Thus, the parallel yet intertwined evolution of the occupants must be identified as 'the house and its occupant mould each other' (Brand,1994). This chapter will focus on the social determinants that shaped the Sudanese house that were discussed in section 2.2. These included privacy, communalism, conformity, lifestyle, thermal comfort expectations and adaptive behaviours such as thermal migration. Figure 5.1 summarises the parameters discussed.

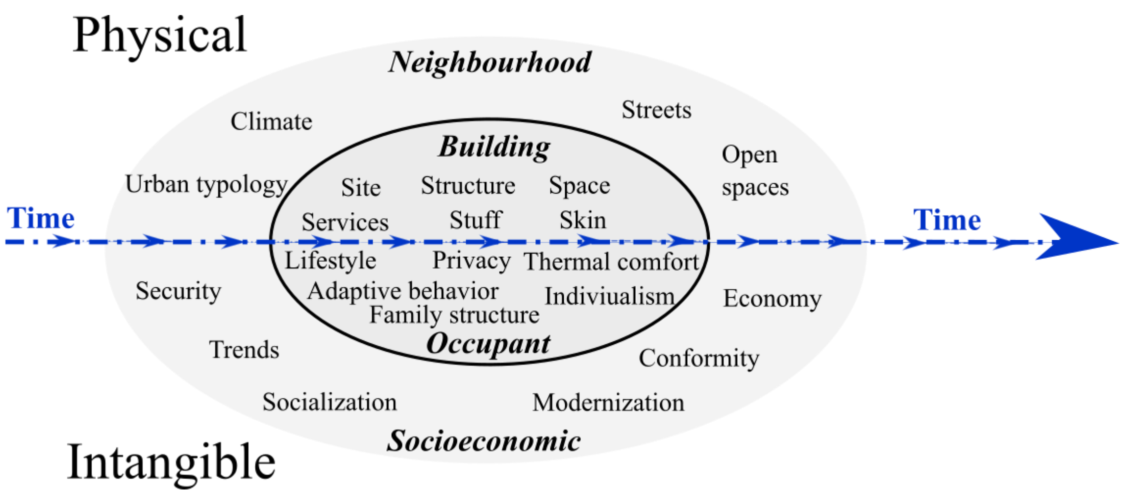


Figure 5.1 Study framework for the case studies

The broader context also includes the neighbourhood, as buildings are not separate from their surroundings. This is especially important in the Sudanese context as the outdoors accommodated male socialization, children playing and social events like weddings, especially in tight urban plots (Ahmed, 1978). As discussed in section 2.2.1, space sequence in the Sudanese home is gradual from the private room to semiprivate shared spaces to courtyards and the street, and the public open space. The relationship between the street design and the building plot is a second impact. In medina style

Omdurman, the street is whatever space remained between the houses; thus, the house dictated the street form. In contrast, in colonial Khartoum, the straight street determined the planned plot size and shape. These different approaches created the two typologies' traditional house' and 'institutional house', as mentioned in sections 2.3 and 2.4.

Stewart Brand has provided a framework for studying the physical evolution of a building. In 'How Buildings Learn'(Brand, 1994), he sets out a framework to understand how buildings evolve by dividing them into six layers, each changing at different time scales. These layers are the site, the structure, the skin, the services, the space and the stuff. The site encompasses both the building and its neighbourhood context. The structure holds the building, so columns, foundations, and structural walls. The skin is the building fabric and external form. The services are the buildings plumbing, electricity and HVAC. The space is the internal arrangement of spaces via ceilings, floors and walls. Finally, the stuff is the ever-changing furniture and décor items like wallpaper. Brand applies his analysis primarily to buildings in Britain and the US (Rodden & Benford, 2003), shaped by a context different from those shaping changes to buildings in Sudan. For example, he states that the site is 'eternal'; however, due to poor regulation and the organic way houses traditionally grew, the plot boundaries are also subject to change in Sudan. The number of years assigned to each layer is also irrelevant due to the lower economic conditions and available technology and materials. Despite these differences, the general framework can be adapted for analysing 'change' in the Sudanese context as it has been used by different studies worldwide (Agha & Jm, 2018).

Our analysis in the previous chapter identified several factors that were key to the success of traditional houses; in this chapter, we will see if these elements have been preserved as part of the buildings' traditional core' (Kotharkar & Deshpande, 2012). Flexibility and adaptability are key elements in several traditional architectures (Estaji, 2018; Kotharkar & Deshpande, 2012). Estaji divides this flexibility into the ability to use the same space with different functions, thermal diversity to facilitate using spaces at different times, and adapting to familial structural changes by growing and subdividing. All three types existed in the traditional Sudanese household.

The courtyard space allowed these different types of flexibility by providing thermal diversity, room for expansion and multi-functionality (Abass et al., 2016).

In the specific context of traditional buildings, studying change can be done through different methods outlined by Nagpur (Kotharkar & Deshpande, 2012). To understand ‘change’ over a long period, several studies use secondary literature to map the evolution of a specific housing typology over time (Aalen, 1966; D. Baker, 1986). This methodology has been demonstrated in the previous chapter by tracing the evolution of the traditional house as it moved from a rural to an urban setting. The second method is a longitudinal study tracking the changes of specific case studies at several points throughout their lifetime (Agorsah, 1986). The problem is that traditional buildings change slowly, enabling scholars to only study a part of the ongoing transformation in their lifetime. An alternative is a chronological study of the building in its current context and retracing from there. Traditional buildings, especially residential ones, are poorly documented and often built without official design plans. Another approach is looking at different usage patterns in current traditional and modern buildings to deduce the changes that occurred. This study combines both methods by utilising a chronological study, which the focus of chapters 5 and 6, and a study of consumption patterns in chapter 7 of this thesis. This helps triangulate the results and show whether the changes are limited to a specific typology or if they reflect a much wider trend. Another widely adopted approach is comparing the same typology in different settings, such as a traditional house in the rural, semi-rural and urban contexts such as the studies (Kotharkar & Deshpande, 2012). This approach wasn’t used because this study focuses on the impact of modernization on different typologies within the same setting rather than the impact of urbanization on a single typology. Limiting the variables is needed to achieve meaningful results with limited resources. Modernization has created a high contrast between cities and rural areas, requiring a large sample to be representative. Cities in different countries are now more similar to each other than rural areas in the same state (Y. Mahgoub, 2013). Thus, findings might be more relevant to other sub-Saharan capitals such as dar-el-salam and Abuja than villages in Khartoum state.

5.2. Selection criteria

As logistic restrictions limit the case studies, their choice must be calculated to ensure they represent a larger population. As discussed in chapter 2, several varieties of courtyard houses exist within the Sudanese context, such as the rural, traditional, and institutional houses. The rural house is irrelevant to the study as we focus on the urban context. Traditional houses are mainly in Omdurman, where the large plot sizes provided by the Mahdi in the late 19th century shaped its expansive and organic nature. Most plots in Khartoum and Bahri and even newer plots in Omdurman are smaller and regular shaped. As this makes the traditional house unrepresentative of a large sample, it has also been excluded from the study. These limitations leave the institutional house or similar courtyard houses built within a regular plot with a size between $200m^2$-$1000m^2$ as our primary sample. The house can be in its original layout or modified as long as its users have shown the adoption of modern life. The building materials must be typical for a courtyard building to provide better representation. Meaning the walls should be brick or mud, and the roof can be thatch or corrugated iron. Concrete roofs, for example, are not typical for courtyard houses, except in a room or two of the house.

This study focuses on AC consumption; therefore, the houses selected must have at least one AC. Both split units and evaporative coolers need to be represented to see the impact of these ACs on a typical courtyard room, which is often very porous. Having an AC in Sudan usually means the family is or was a middle-class one. The occupants should be an extended family in some cases, and nuclear in others to both reflect different stages of the growth of a Sudanese household and need to be represented. The occupants must be the original owners or descendants to provide as much detail as possible about the thought process guiding construction and modifications. The occupants must be Sudanese, as the study's social and cultural factors are essential. The occupants can be originally from Khartoum, expats or from other Sudanese states, which helps show the impact of different backgrounds. Finally, the occupants are acquaintances of the author or their family, as the study involved monthly updates, several interviews and expensive equipment, which would be hard to manage otherwise.

The three buildings, T1, T2 and T3, are located in Khartoum in planned neighbourhoods, as shown in Figure 5.2. Each neighbourhood has a different history that influences its design, street width and available open spaces that will be explored later.

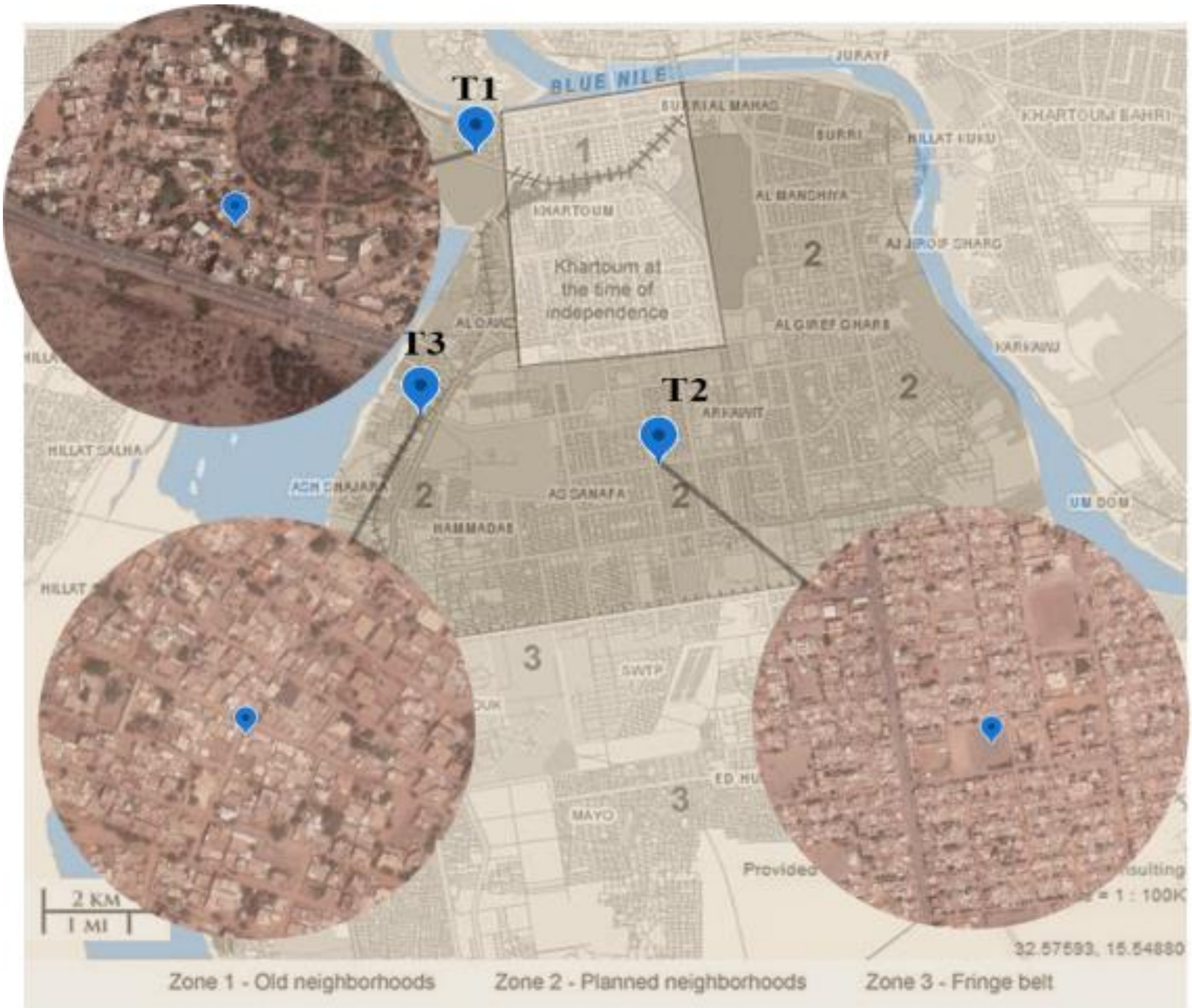
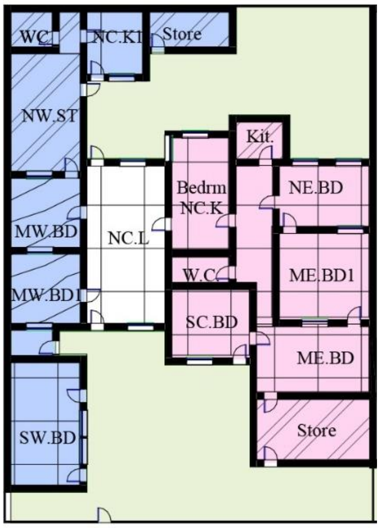
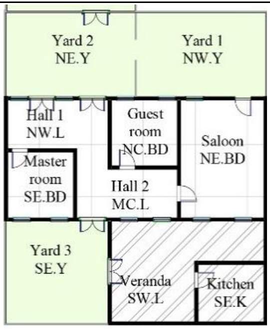
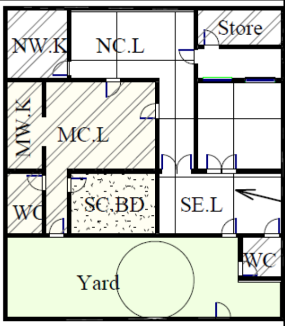


Figure 5.2 Locations of T1, T2 and T3 within Khartoum

Table 5.1 Overview of the properties of the case studies T1, T2 and T3.

		T1	T2	T3
Floor plan				
Photo				
Built in		1950s	1960s	1990s
Occupants		7	6	4
Area m^2	**Built**	389	185	140
	Unconditioned	93	35	53
	Conditioned	140	100	52
No. of rooms		10	6	5
Yard surface		Concrete tiles	Ceramic tiles	Ceramic tiles

5.3.Case study 1-T1

Overview

Figure 5.3 Al Mogran neighbourhood

Al-Mogran is one of the oldest planned neighbourhoods in Khartoum as it is right beside the original small town Mclean designed in 1912. Most houses in the neighbourhood are ageing, both courtyard houses and modern ones, as shown in Figure 5.4.

Figure 5.4 Photos of the buildings surrounding T1

Figure 5.3 shows how the residential buildings are slowly being replaced by commercial buildings (in blue) such as the one shown in Figure 5.4, especially offices and banks, due to their prime location. There are now few neighbours remaining. The national botanical garden, built in 1954, is the heart of the neighbourhood as the plots all radiate from it as the centre, as shown in Figure 5.3. As the area has two highly vegetated areas nearby, the botanical garden and the Sunut forest to the south, it has a large mosquito population. During the flooding season, the area is sometimes submerged in knee-deep water, which causes a lot of damage to the old buildings. It is one of the few areas in Khartoum with a working sewer system.

Figure 5.5 Left: photo of outer courtyard in T1. Right: photo of inner courtyard in T1. Taken by the author

T1 is a 402m^2 traditional building built in the 1950s. Figure 5.5 shows the house from the outer courtyard. The courtyard floors are paved with concrete mosaic tiles, and it has a bed to be used during power cuts. The traditional Rakoobas (straw veranda) shown in the photos need repair as Rakoobas tend to need constant maintenance. Despite this, the shade underneath it is cool and aided by the pot plants. The inner courtyard is used as a service yard for laundry. The nuclear family that moved in started with seven children. The current occupants are those children with their 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, which is why it is a mismatch of different materials. This problem is evident in Figure 5.5, which shows how the left and right rooms are higher and better finished than the middle section. The middle section was a courtyard, later closed off, while the other rooms were part of the original construction. In 2017, their western neighbour cut down the tree that used to shade the roof of the room SW.BD (Figure 5.5). The occupant, complained that the room became significantly hotter afterwards, which further highlights that buildings are impacted by their surroundings.

Evolution of T1

This section explores the socioeconomic and environmental aspects of the house's evolution. The trigger event that started the phase is identified in each stage, along with the drivers behind each change and the environmental impact. Previous chapters have addressed these drivers: the need for more space, security concerns, and a modern house aspiration. The researcher was able to stay in the building for several weeks as the residents are close acquaintances; this enabled T1 to have the most details in its history and current use patterns.

People's background often influences their choices, so it's a good starting point in understanding a house's history. The Family in T1 were upper-middle-class and frequently travelled due to the father's job. This wealth gave them access to modern construction materials and air conditioning as early as the 1960s. In one of their previous houses in Alamarat, an upper-class neighbourhood, they had evaporative coolers in every room but only used them when needed. Most were no longer functioning due to age, and only three worked. They had less air conditioners when they initially moved to their current house because the rooms were back to back which limited access to external walls to install the AC on.

They spent most of their time together in the southern living room as it was cool. The veranda was also cool all year round as an adjacent building shaded it. The family used the outdoors to cook during intense cooking sessions and sometimes sleep. The father always slept outside in a mosquito tent as that is where he grew up sleeping. According to his children, he closed the verandas in every house they moved in for safety reasons and ensured his children slept indoors. The courtyard house had metal roofs and false ceilings. Figure 5.6 shows a plan of the house.

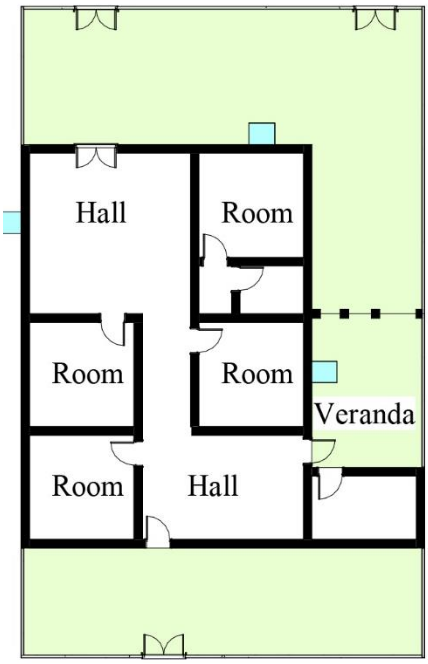


Figure 5.6 The Amarat house the residents in T1 lived in before the current house

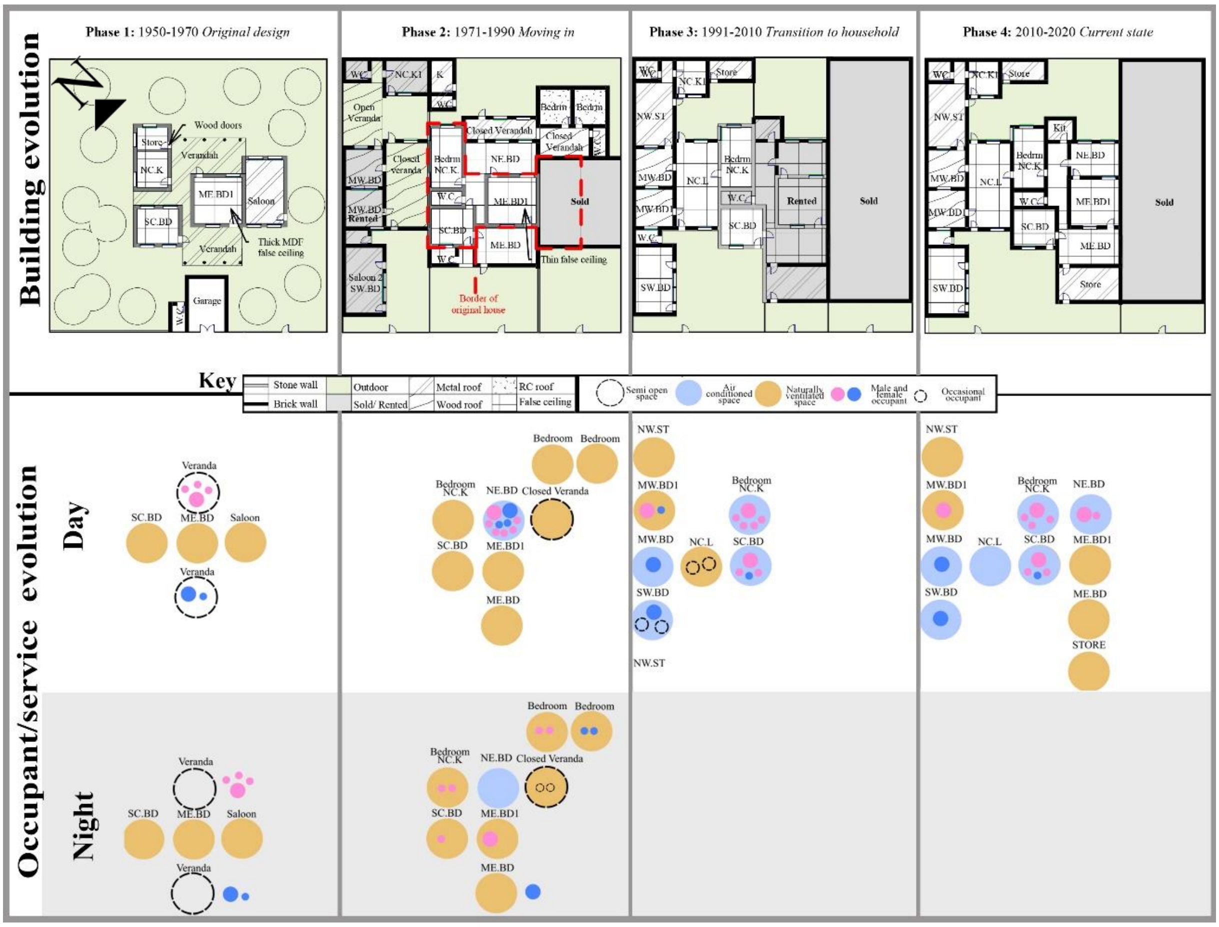


Figure 5.7 The evolution of T1 by author

The house went through 4 phases, each lasting 10-20 years, as shown in Figure 5.7. The figure maps the building's changes in the upper part and the services and occupants in the lower one. It slowly transitioned from a small house surrounded by the outdoors into an extended structure with two small yards. The built area increased from 14% to 70%. To suit the users' needs, it constantly went through additions of spaces, sectioning for rent or new living arrangements, material changes, height changes and closing of semi-open spaces. The air-conditioned rooms slowly increased from just one in phase 2 to six in phase 4, or 75% of used spaces. Sleeping outdoors stopped in Phase 2.

The house was originally built by a wealthy Egyptian man who rented it initially. This reflects Khartoum's colonial past as areas near the town's centre were reserved for Egyptians and other Arabs, as mentioned in section 2.3. In the initial phase in the 1950s, the house had a low wall marking its external boundary, a typically rural feature as rural areas are safer than cities (Ikudayisi & Odeyale, 2021). Another sign of the sense of safety was that the bhouse had an open design with scattered rooms linked by two verandas (Figure 5.8).

Phase 1: 1950-1970 *Original design*

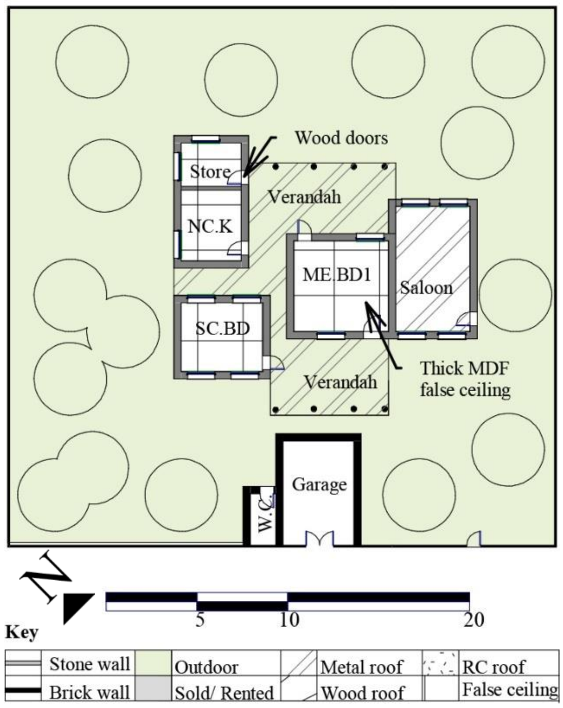


Figure 5.8 Building Phase 1 of T1 from 1950-1970

This layout meant the occupants would have to step into a semi-shaded space every time they moved from one room to the next, facilitating a smooth and constant connection with the outdoors. The kitchen was under the same roof as the rest of the house rather than on the boundary wall, a typically colonial feature.

The outdoor space was inviting and encouraged occupants to spend time outdoors. It was used for physical activities: sitting on the swing, taking care of the chickens, taking care of the fruit trees, all activities that require space. The large yards in the original house would have also provided shaded zones at other times of the day, expanding the possible time spent outdoors under cool conditions. The original vegetation, which included a large tree, provided shade for the building from the intense sun.

The stone walls had a thick MDF roof and wooden windows and doors with a mosquito mesh. The built-in mosquito mesh allowed them to leave the windows open at night to cool the building if they chose to sleep indoors. The household head was interested in maintaining the house generally and promoted traditional behaviours like moving the beds outside in the evening.

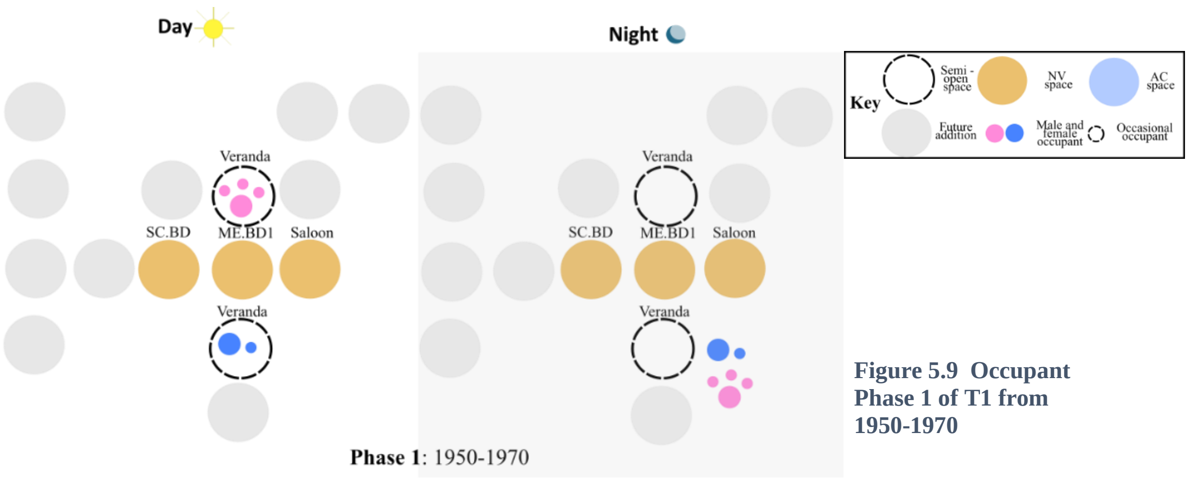


Figure 5.9 Occupant Phase 1 of T1 from 1950-1970

The verandas had a colonial aesthetic (Figure 5.11) with concrete columns and a metal roof rather than a traditional Sudanese straw rakooba. The verandas were open, meaning that one or more sides had no walls. A veranda is considered a ‘closed veranda’ when that open space becomes enclosed, usually with a small brick or metal wall with the remainder covered by a metal mesh of windows. Closed verandas provide safety while maintaining more ventilation than rooms.

Figure 5.11 The original columns that held the veranda of the original house in T1

Figure 5.10 A photo of a wooden roof in T1

The second phase started after the current family moved in during the late 1970s, which was a financially difficult period in Sudan, as mentioned in section 2.5. The family needed more space to accommodate their larger size and extra income by selling and renting portions of the house (grey areas in Figure 5.12). To do this, they built new closed and open spaces, closed off existing verandas and converted the Kitchen NC.K into an extra bedroom, while the family used a small kitchen (K) on the northern perimeter wall. Closing off the verandas made the room ME.BD1 lack any external walls, which reduces the efficiency of cross ventilation and the ease of installing an evaporative cooler. Dark and poorly ventilated spaces are a well-documented consequence of closing off verandas and outdoor spaces (Aksoylu, 1987; Brand, 1994). The expansion also reduced both the amount and quality of outdoor space available. It created several smaller yards that could no longer support trees and animal pens.

Phase 2: 1971-1990 *Moving in*

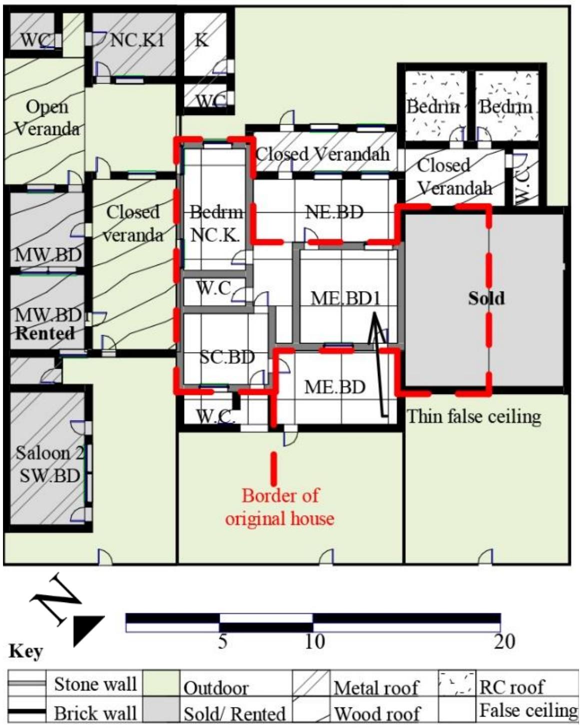


Figure 5.12 Building Phase 2 of T1 from 1971-1990

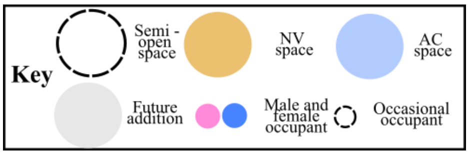
The extensions were not built in the same materials as the original house. Cost rather than thermal performance was the key driver in choosing the new ones. The walls of the extensions were constructed using thinner brick walls rather than the original stone. The original thick MDF was removed to increase the building's height and replaced with thin MDF in most rooms. The new additions: MW.BD1, MW.BD and the two verandas to the west had wood roofs (Figure 5.10). Wood was cheap at the time as it was imported from South Sudan before the succession (Adam, 2002), which highlights the supply chain as a critical driver.

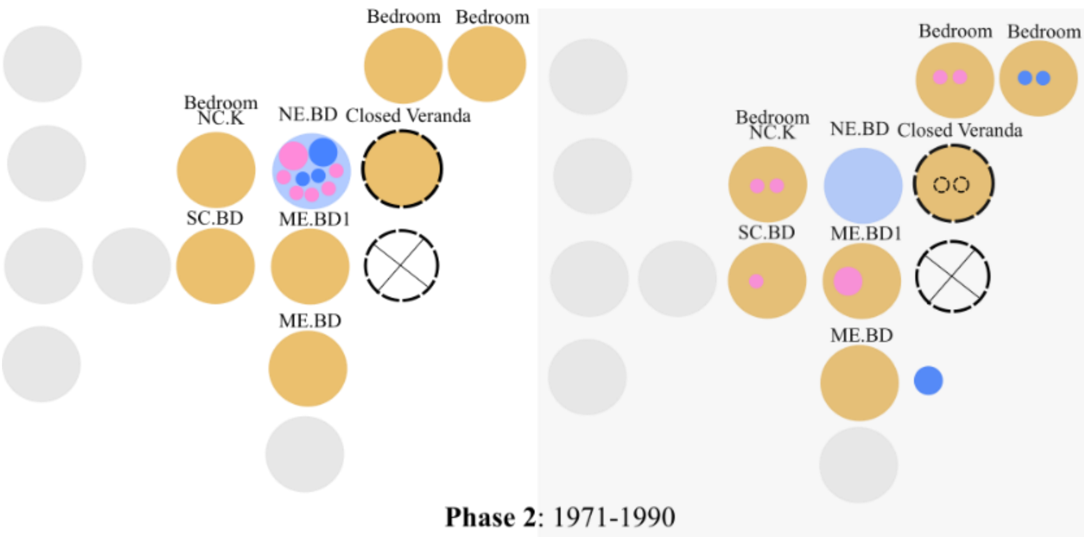
However, an aspiration for modernity rather than cost is behind choosing concrete roofs for the two northeast bedrooms, labelled Bedrm. The owner had already built up most of the land and wanted to start expanding vertically. He planned to add stairs and build above the two rooms. Due to the lack of finances, he planned on adding concrete spaces slowly until he replaced the entire house. One of the occupants reported that the unconditioned concrete bedrooms got so hot that *'you would wake up with the sweat lining where your body was on the bed'*. The two bedrooms were linked to the rest of the house by two very hot, closed verandas for safety purposes. The family chose to sleep in them at night, which likely means it was cool at night due to the rapidly cooling metal roof and the fact it had an exposed wall that could cool faster than the inner walls.

Concrete screed covered the yard as it was easier to clean, saving time, an essential requirement for a faster-paced modern lifestyle. The occupants complained that it retained heat and didn't cool as much when they sprayed the yard. This complaint could have contributed to the family sleeping less outdoors during the 1980s and stopping entirely in the 1990s, in addition to the safety concerns. All the wooden doors and windows with metal for added security; however, the mesh was not replaced. Therefore, it was no longer convenient to open the windows at night. During this phase, the occupants ceased to use adaptive behaviour and instead made increasing use of air conditioners.

During the day, the entire family stayed in the shared conditioned living room (NE.BD) to use the AC and slept in the rooms or the closed veranda, as shown in (Figure 5.13). Fans were left on whenever the room was occupied. On the rental side, a window unit was installed in SW.BD, which was a guest reception. It was a gift from abroad and was not common during this era.

Figure 5.13 Occupant Phase 2 of T1 from 1971-1990





Phase 3 began when the family evolved into a household family, needing even more space. They accomplished this by changing the space use configuration and closing off verandas. They moved to the larger west side and rented the smaller flat in the east. As the east side was small, the renter decided to haphazardly add a poorly constructed kitchen and room in the south, creating four back-to-backspaces. This room can be seen in Figure 5.16. The two additions have metal roofs and are so hot that the occupants currently use them as stores. A common problem in courtyard houses, renters have little investment in the house and are less inclined to pay for expensive materials.

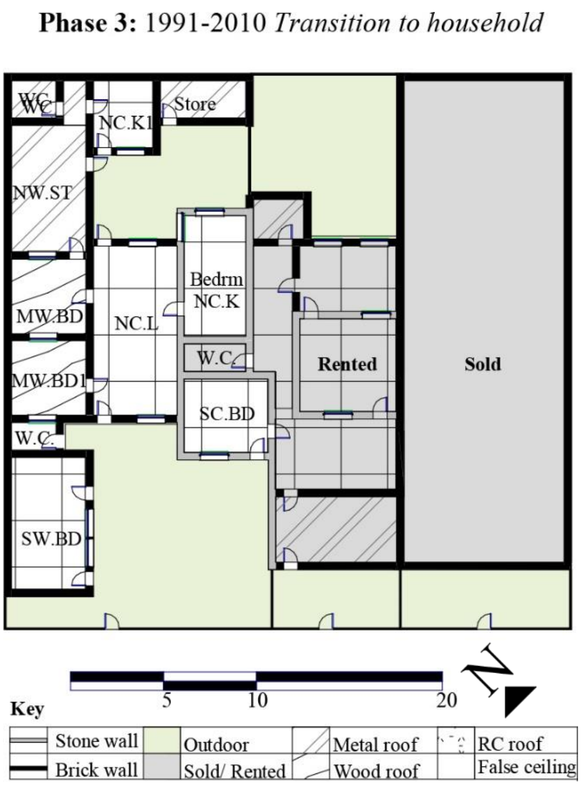


Figure 5.14 Building Phase 3 of T1 from 1991-2010

On the west side, the closed veranda that used to link the two sides safely needed to be converted into the habitable space (NC.L). So, they added walls and a false ceiling and paved the floor. The open veranda used to be a cool extension to the kitchen, a common feature in Sudanese homes. As it was closed without a false ceiling, it became too hot to be used as anything other than a store, just like on the east side. Another common aspect was that the conversion of the two verandas also created spaces that no longer had external walls. The thin roofs heat the room and walls during the day, which cannot cool efficiently at night because of the reduced ventilation.

Initially, only the household head's room (MW.BD) had an evaporative cooler, despite him still sleeping outdoors. The grandchildren mentioned that the house used to be hot and uncomfortable and would spend as much time as possible in their grandfather's conditioned bedroom. The family structure change impacted how the spaces were used. The close family relations in Phase 2 meant that one conditioned room for the entire family to use was sufficient. In phase 3, the younger generations needed more privacy, especially since they became separate family units. So the conditioned spaces became private bedrooms and not the public living room during this phase; evaporative coolers were added to SC.BD and NC.K. (in 2004). The most used areas changed from zones dedicated to the communal main extended family to the individualistic smaller nuclear families' zones. Space usage no longer had a day/night distinction as the family depended entirely on the AC. A notable mention is that the family frequently received lodgers. Male lodgers shared the saloon (SW.BD) with the son while female ones slept in the female-only rooms. The saloon's location allowed male residents easy access to the outdoors without invading the inner house's privacy. The saloon AC was replaced with an evaporative cooler, like the other ones in the house.

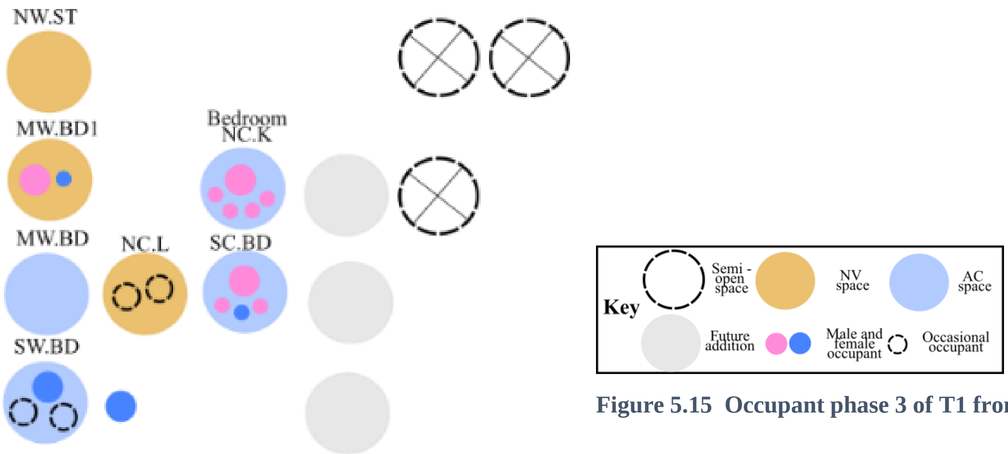


Figure 5.15 Occupant phase 3 of T1 from 1991-2010

Figure 5.16 A photo of T1 showing the haphazard extension built over the boundary wall

Finally, by 2010, the family ceased to rent out and expanded their usage of spaces into the current form. Phase 4 is different from the other phases in that the most significant change is in the occupants rather than changes to the house. The phase begins after the death of the household head, who was responsible for taking care of the house and maintaining it. This responsibility wasn't transferred to a specific individual, which can later be seen in how deteriorated several house elements are in section 8.5.1. The yard was no longer sprayed, so they replaced the screed with concrete tiles. The feeling of responsibility and ownership towards the house diminished with each generation. During the interviews, the older residents complained that, the younger ones did not monitor their consumption; they wanted their own space. The youngest occupants said the lack of privacy and control over their environment makes them feel the house is not worth investing in by saving money through energy conservation behaviours. The older occupants also did not have their own spaces growing up, but that was the norm, which is probably why they still felt responsible for the house. The researcher observed that the TV is no longer the focal point, especially for younger generations relying on their phones.

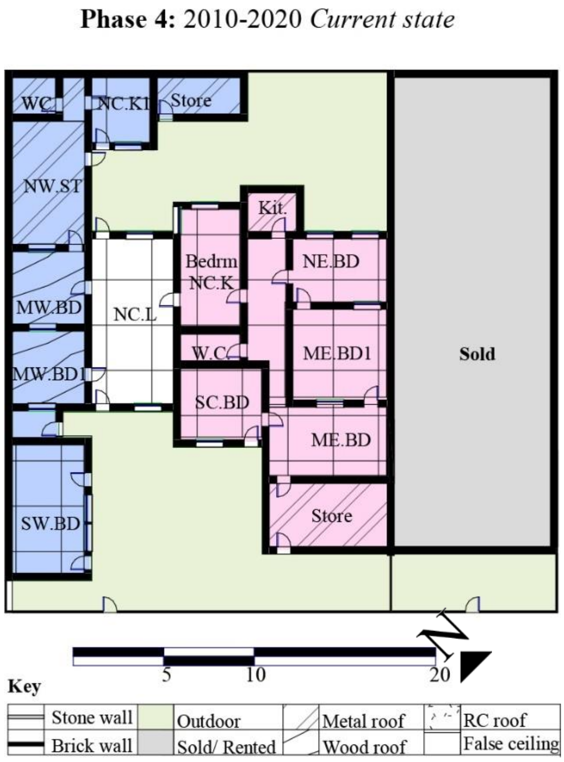


Figure 5.17 Building Phase 4 of T1 in its current state 2010-2020

The unplanned expansions and modifications have led to a privacy problem in the house, as most rooms had two doors. The only rooms with one door were reserved for the two males (a son and grandchild). Both of whom turn the air conditioning on whenever they are at home. This trend could signify the male's disassociation with the family, exacerbated by their physical distance from the rest of the house.

The remaining members are from different nuclear families; thus, instead of dividing spaces based on each nuclear family, they were split into male/ female sides. The males occupy the west and the females the east. The Kitchen (NC.K) was restored into a kitchen in 2020 due to its central location that both sides can use. Another reason was that the northern kitchen (NC.K1) was sweltering and small; it was not meant to function without the open veranda.

Despite reducing the number of occupants, the number of conditioned spaces increased to 6. The family added two more evaporative coolers in NE.BD and the living room NC.L. A split unit was added to ME.BD to compensate for the lack of ventilation there. However, the house's old electrical supply could not sustain it. They also could not install an evaporative cooler because of the lack of external walls. In 2020, they tried again by moving it to SC.BD used it during the day when the evaporative cooler wasn't cooling enough, but it eventually failed again. The evaporative cooler also triggered the primary occupant's allergies and had to be used before she returned home at 7 pm.

The family used to leave the windows open at night. Due to security concerns, the users now only open the windows in the morning during cleaning until it gets hot at noon. When the unemployed resident must leave the house for an errand, she waits until someone returns home, as it is unsafe to leave the house empty. This behaviour has energy implications as the house is never empty.

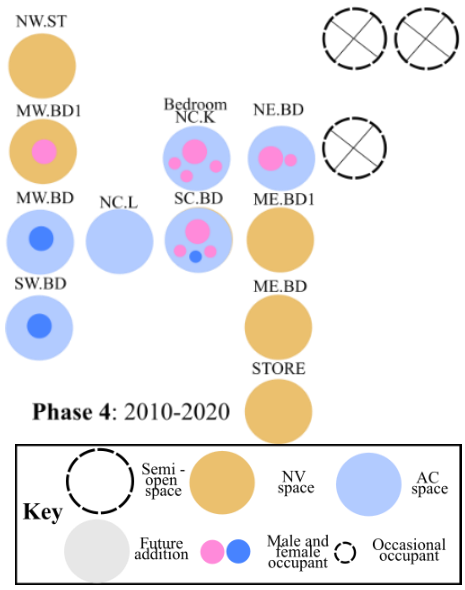


Figure 5.18 Occupant phase 4 of T1 from 2010 to 2020

The house has the main front yard and a smaller back service yard for laundry and storage. The concrete screed was replaced with concrete tiles, as shown in Figure 5.5. On the outdoor level, the newly built high-rise building shown in Figure 5.4 invaded the family's privacy. It limited their yard use during the day and evening, even during a power cut.

In the future, the family plans to demolish the store (Figure 5.16) built by the tenants and replace it with a veranda covered in nets. The aim is to shade the building and provide a cool place to stay during power cuts. The family's long-term plan is to demolish the entire house and replace it with a multi-apartment building.

5.4.Case study 2-T2

Overview

Figure 5.19 Al-emtidad neighbourhood

T2 was added midway through the PhD as the T3 suddenly could not participate in the year-long monitoring. This last-minute addition made the information less available as only two interviews were conducted with the residents. T2 has six permanent occupants. Like T1, it houses the remaining members from different nuclear families. There is a working mother with her two daughters in college. Her sister stays some days to ensure the house isn't empty. Their elderly uncle stays in the saloon with their niece, who also works. The family members have lived in this house since birth and do not remember a time before that.

Al-emtidad is an old neighbourhood built around 1955-1970. Its name means 'the extension', most likely because it was an extension to the original 'deims' government scheme (see section 2.4) that is directly adjacent. The occupants said the government gave them the house design when they bought the plot. It is a planned neighbourhood with 200 m2 plots for working-class residents. The streets are straight and wide, with integrated open spaces, as shown in the right photo of Figure 5.20. The area is beside a commercial road highlighted in blue in Figure 5.19. These high buildings can be seen in the upper photo in Figure 5.20. Most neighbourhood buildings have the same design and are all institutional houses, as shown in the bottom photo in Figure 5.20.

Figure 5.20 Photos of the houses and streets surrounding T2

In Early 2022, the southern neighbours demolished their property, making the occupants feel like their adjacent closed veranda was 'exposed' and unsafe. So they stopped using it and moved the TV indoors, which shows that their perception of the neighbourhood's safety changed. An occupant in T2 said:

'*There's no safety. We have open borders now and so much more people. In the past, I used to always have Sudanese neighbours, but now both left and right neighbours are Ethiopians. Families are selling their houses to expand. Houses used to have the grandmother and extended family but now people have sold their lands to buy bigger plots to expand for the newer generations. The family size has increased.*

Researcher*: Has this affected you relationship with your neighbours? Did you know them previously?*

Occupant: *Yes, like I said they all sold their houses. All of them are now Ethiopians, who are renters, owners have become rare, or the original owners sold the house to new people who we're not familiar with. It's also changed our relationship with people. We only visit if there's a purpose now. The economic situation has changed too. You only let people in if you have to now, in the past we used to share everything. In the past, it was quite normal for your neighbour to call and ask for a plate of food, that doesn't happen now*.'

Figure 5.21 Photos of the yards in T2 taken by Author. (Right) The back yard SE.Y. (Left) the front yard NE.Y

T2 is an institutional house built in the 1960s; the plot size is 300m^2. Figure 5.21 shows the house from the courtyard. The courtyard floor is paved with ceramic tiles and has several beds to be used during power cuts. Mattresses are kept indoors to prevent them from getting dusty. The large doors are where the veranda was previously open. There are only a few scattered plant pots.

Figure 5.22 shows the male courtyard NW.Y. The photo shows a nearby multistorey building overlooking the yard's privacy; the window position is legal as it is a stairwell, not a habitable space.

The family living in the house is an extended family that started with two parents and eight children. As the original plan provided by the government already filled the property, most changes made to the house are mainly materials changes or switching functions. The home is segregated into a male and female side, with the saloon always housing various male lodgers.

Figure 5.22 A photo of T2 shown from the male courtyard NW.Y

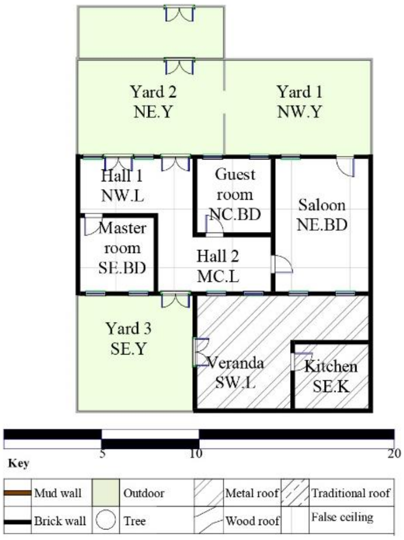


Figure 5.23 Plan of T2

Evolution of T2

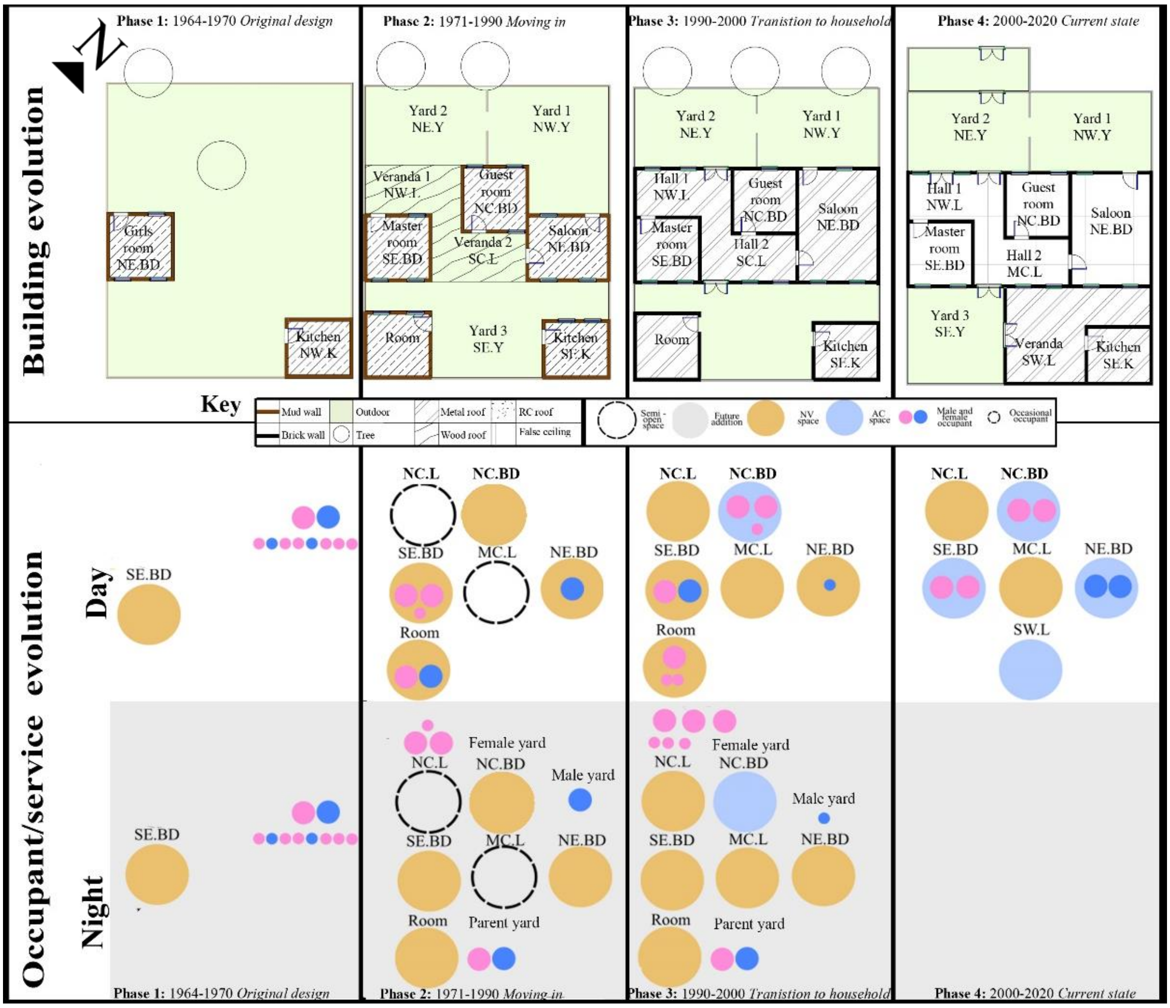


Figure 5.24 The evolution of T2

Figure 5.24 shows the evolution of T2, which also went through 4 phases. However, unlike T1, the expansion was minor, and the internal area increased from 33% to 61% of the property. The main change was in the building material, cooling methods and occupants' lifestyle. The airconditioned spaces gradually increased until all the main used rooms became airconditioned. Sleeping outdoors stopped later in phase 4.

In the initial phase in the 1960s, the family started with one room and a kitchen before gradually adding the rest of the rooms. They followed the design given to them by

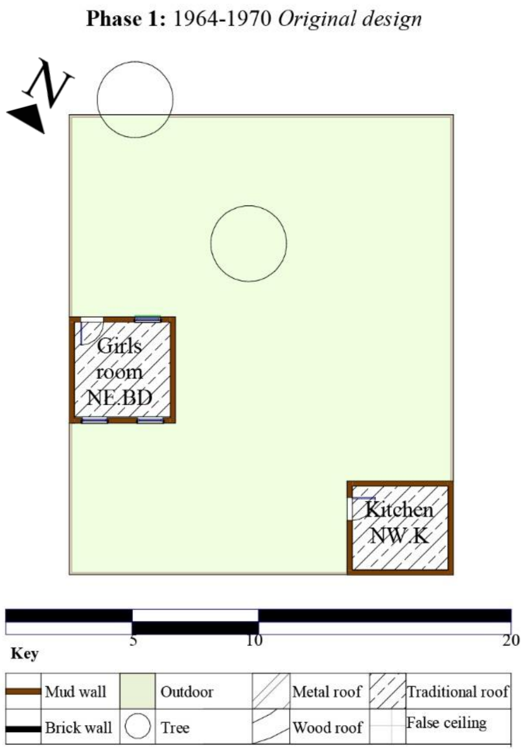


Figure 5.25 Building Phase 1 of T2

the government to guide the additions. They used mud walls and a traditional thatch roof like T3. The family spent most of their time outdoors under the shade of the tree in the yard while construction was completed. They also had chicken and goat pens. The family consisted of two parents and eight children.

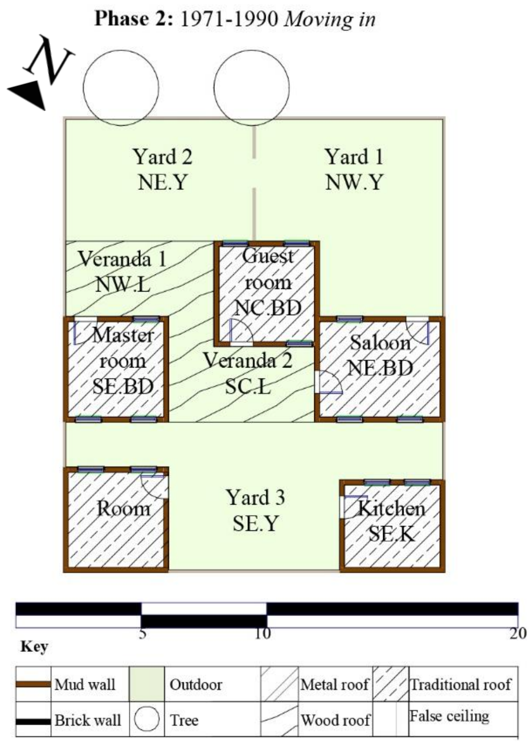
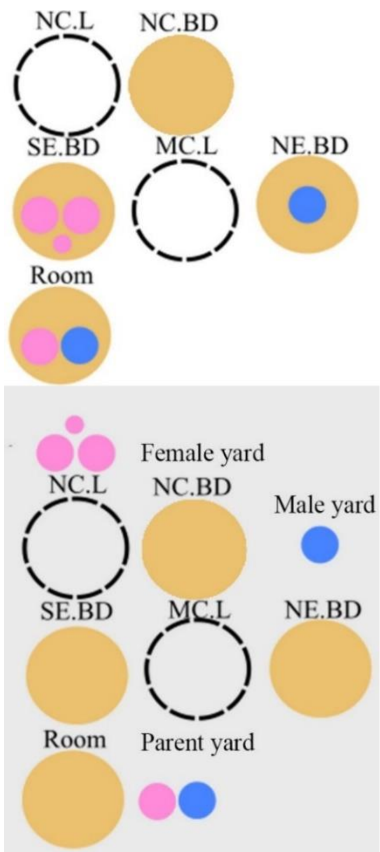


Figure 5.26 Building Phase 2 of T2

The second phase started when the family became an adult family, and the children needed more privacy. The house construction was completed and now had a saloon, three bedrooms and a kitchen. Two verandas were added that were made of wood. The flooring was bare earth both inside and in the yard. The tree in the middle of the plot had to be cut to allow construction but was replaced by two trees on the street. The house was still mud and thatch.

The family lived a communal lifestyle where gender segregation was critical to space use patterns. The males had the saloon with Yard 1. The parents had the southern room with its Yard 3. The females used SE.BD and its yard. The occupant’s day involved going to school/work during the mornings, followed by time spent in the rooms and veranda during the afternoon. By 3 pm, they start spraying the yard and preparing to sleep in it, with each person sleeping in their respective yard.

Veranda 2 acted as the living room; it was cool without needing fans. The neighbourhood was safe enough to leave the TV in that open space.



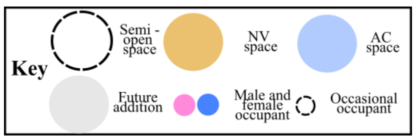


Figure 5.27 Occupant Phase 2 of T2

The third phase marks the family's transition from an adult family phase to a household phase. During this phase, the family comprised of the parents and their three adult daughters, who had remained with four grandchildren. During the 1980s, the eldest son became an expat and helped fund the house's complete renovation in the 1990s, which is an example of the indirect impact of expats on housing in Sudan. The direct influence came from the modern houses they built for themselves when they returned.

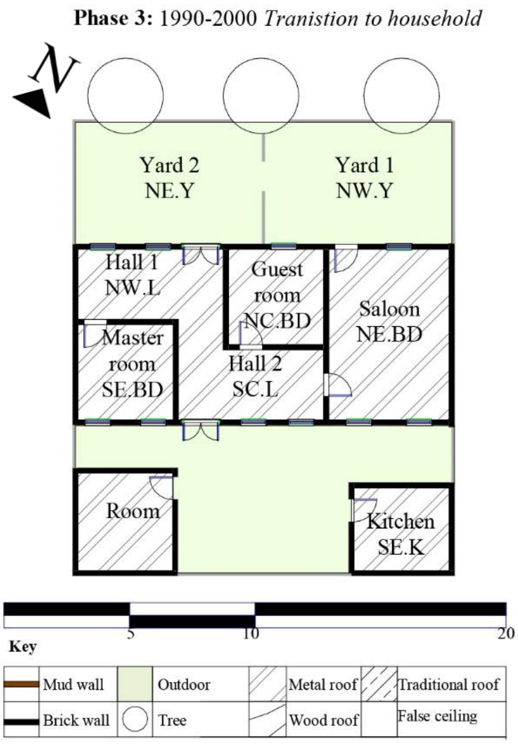


Figure 5.28 Building Phase 3 of T2

The saloon was extended to accommodate male lodgers, a requirement of the household phase. Like T1, the verandas were closed off between phases 2 and 3 into halls. However, unlike T1, this driver was not the need for additional space but rather to keep up with the trends. The occupants' busy lifestyle meant that the regular upkeep of the veranda became tiring, especially the dust accumulation. The occupants shared this complaint in the modern houses as their reason for decreasing outdoor space use. Changing the floor finish to concrete screed indoors and outdoors also helped with this aspect. The concrete was covered with vinyl in the interior to make it more visually appealing. The occupants were fully aware of the negative thermal impacts of their material change. The concrete floor needed to be sprayed twice (at 3 pm and in the evening) because it retained heat. The natural earth only required to be sprayed once.

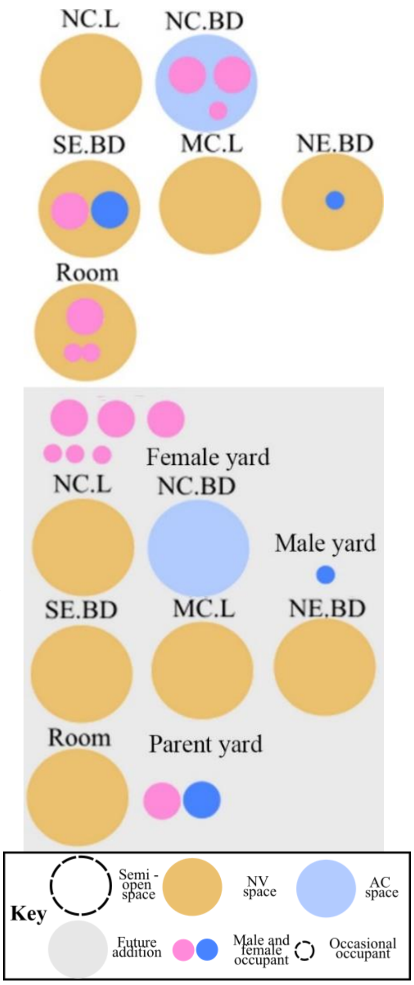


Figure 5.29 Occupant Phase 3 of T2

People are 'symbol-users' meaning that, their building material and appliance choice is driven by status expectations, in addition to utilitarian functions such as energy efficiency or thermal comfort (Lutzeinhiser, 1993). Hosham noted that despite occupants being thermally comfortable in their traditional homes, they aspired to modern ones (Hosham & Kubota, 2019). This desire to modernise drove the users in T2 to change the building materials from traditional ones like mud, thatch and wood to brick and metal. The occupant said that before the material change, they only needed a fan to remain cool. These fans were installed during the renovation in the 1990s. Status often takes precedence over comfort, in Barriadas, people invest in expensive doors but delay building a permanent roof up to two years later (Rapoport, 1969).

Another coping mechanism was installing the first evaporative cooler in the guest room in the early 2000s. They used to leave the doors open so the cool air could reach the halls and saloon, a prevalent habit also used in T3 today. In an interview with an air conditioning expert, he mentioned to the researcher that people had transferred this habit to refrigerant air conditioners, which become overloaded, having to cooler a much larger space, causing excessive consumption. The family still slept outdoors, however, less frequently.

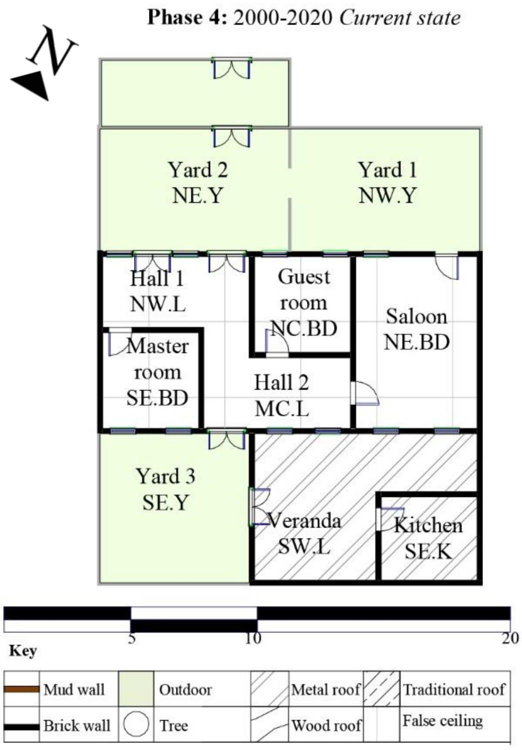


Figure 5.30 Building Phase 4 of T2

Phase 4 is the house's current state. Both parents had died, but an older relative was taken in. The family comprises the remaining members and visiting members during the weekend. Like T1, the kitchen was small and uncomfortable, so they decided to demolish the room and replace it with a veranda SW.L in front of the kitchen. This veranda has metal roofs and walls, as shown in Figure 5.33. A small extension was made near the entrance wall to accommodate additional lodgers during events, as shown in Figure 5.32. The excessive heat from the metal roofs required the users to add false ceilings. The vinyl was expensive to replace every year, and thus ceramic tiles became a better option. They also became more accessible because they had become more popular. The yard was also paved with these ceramic tiles, as shown in Figure 5.33. The metal roof was hotter than the wooden one, so a false ceiling needed to be installed. Adding a false ceiling to increase insulation was seen in houses in Sudan since the 1970s (Elias, 1970).

This phase saw the addition of 3 evaporative coolers in the saloon, master room, and veranda. However, the master room evaporative cooler does not currently work, and the one in the guest room was fixed to cope with Ramadan of 2021. The family sleeps indoors entirely, with the men sleeping in the saloon and younger females sleeping in the master room.

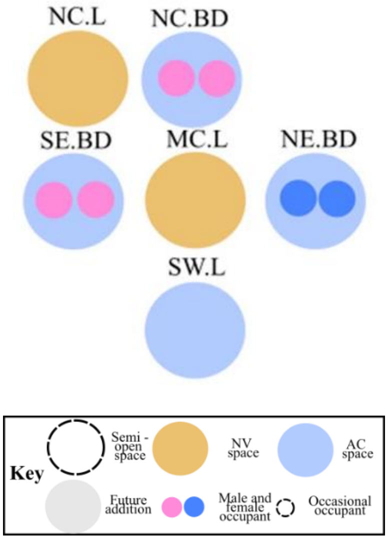


Figure 5.31 Occupant Phase 4 of T2

The occupant reflected on the differences in AC use between her generation and her Gen Z daughters: *'They don't adjust like us. We adapt to any environment, with or without the AC, we don't necessarily need it. On cool nights, fans are enough for us. But they turn the AC on and cover themselves in heavy blankets'*.

Overcooling is a new trend in many countries in the global south (Alnuaimi et al., 2022). She also complained that the girls also do not ensure they turn off the evaporative cooler and lights when leaving the room. When asked if they actively limit the younger occupants consumption she replied: *'Yes we do, we don't allow them to use it all the time'*. The family said their consumption is moderate and does not exceed 400 kWh. The introduction of the TV in Sudan led to families becoming more 'home oriented' since the 1970s (Elias, 1970b), opting to spend time indoors more than on social outings. Within the house, watching TV took precedence over thermal comfort (Merghani & Hall, 2001). The significant impact TVs have on usage patterns is also seen in T2. After the TV was moved indoors, the family no longer used the closed veranda SW.L. The occupants used to open the window at night when it was safe in the past. They currently only open them during the morning to air the house.

Figure 5.32 A photo of a small extension to house lodgers in T2

Figure 5.33 The veranda SW.L with metal walls and a roof

5.5.Case study 3-T3

Overview

Figure 5.34 Location of T3 showing the surrounding amenities.

T3 was a participant in the author's previous study as H5 (Elsherif et al., 2020). Therefore, though they could not participate in the monitoring, data from that study can help understand how it performs thermally. The family is composed of 2 parents and five daughters. The mother died, and the father remarried, which created a separate zone for the parents. All the daughters are married and moved out, the last one during this study in 2021. Therefore only a female lodger and the two parents remain.

Al-Lamap is a neighbourhood located to the west of Khartoum, on the banks White Nile. The urbanization maps shown in section 4.2.1 reveal that up to 1990, Al-Lamap was a squatter settlement upgraded to a spontaneous settlement. Hence the irregular grid that is shown in Figure 5.34. This background makes it an excellent example of housing decisions made without the guidance of laws, a common theme in Khartoum. The lack of setbacks combined with uncontrolled expansion meant neighbours frequently shared low walls or walls with high windows. In the past, this allowed for conversations through the wall. However, like in T2, the neighbours no longer know each other. Thus, the occupants complained of the lack of auditory privacy.

Figure 5.35 A photo of the neighbourhood in al-Lamap

The streets in this area are tightly packed, ranging from 6-12 meters wide. The houses in this area are all traditional courtyard houses as this is a high-density lower/middle-class neighbourhood as shown in Figure 5.35. However, as it is a central location, some multi-story buildings as the one shown are being built. As the neighbourhood was not planned, open spaces are scarce, with the nearest one being 0.5km away from the house. Though the plot is large, the east side is left empty to be sold or for the children to expand in if needed.

Figure 5.36 Left and Middle: Photos showing the interiors in T3, they show the false ceilings, the ceramic tiles and the evaporative cooler. Right: Photo showing the concrete tile yard with the one remaining tree

T3 is a courtyard house built in the 1990s on a 240sqm plot. The family is one of the original families in Khartoum. Before living in this house, the family lived in a small 200 m2 plot in central Khartoum near Abu-Hamama. The house was a typical institutional house with two back-to-back rooms with a veranda and kitchen. They were from a lower middle-class family and lived a traditional lifestyle during that period.

Evolution of T3

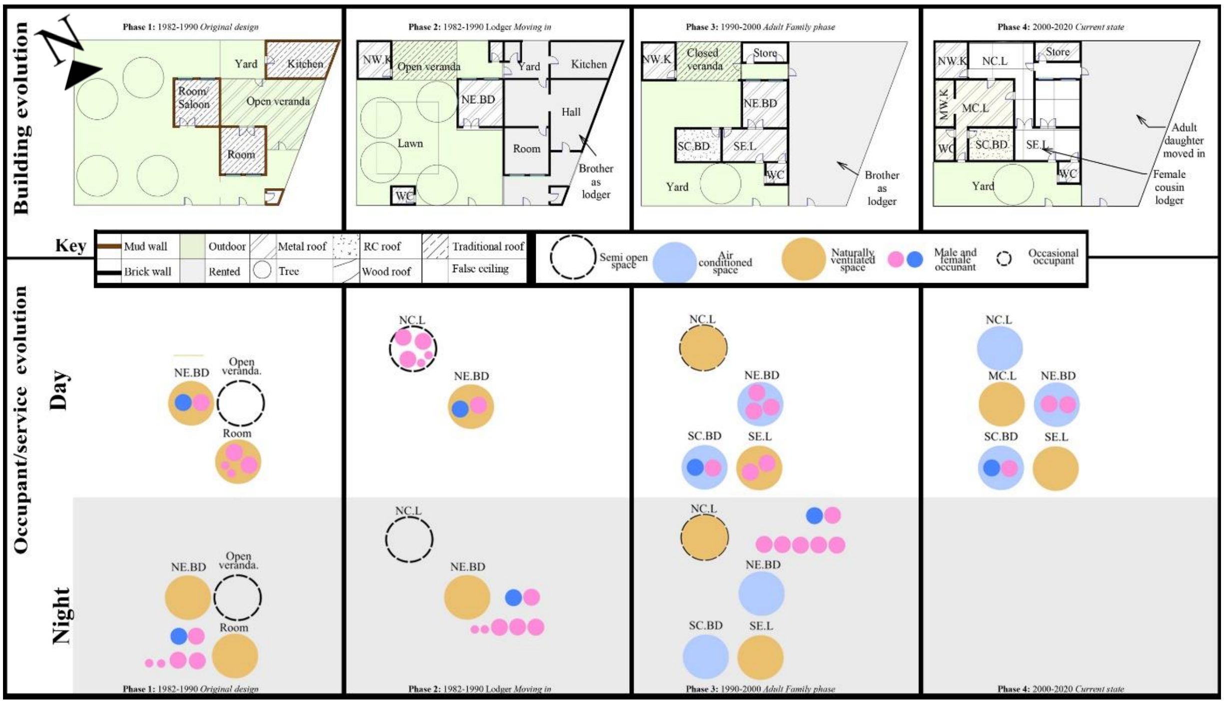
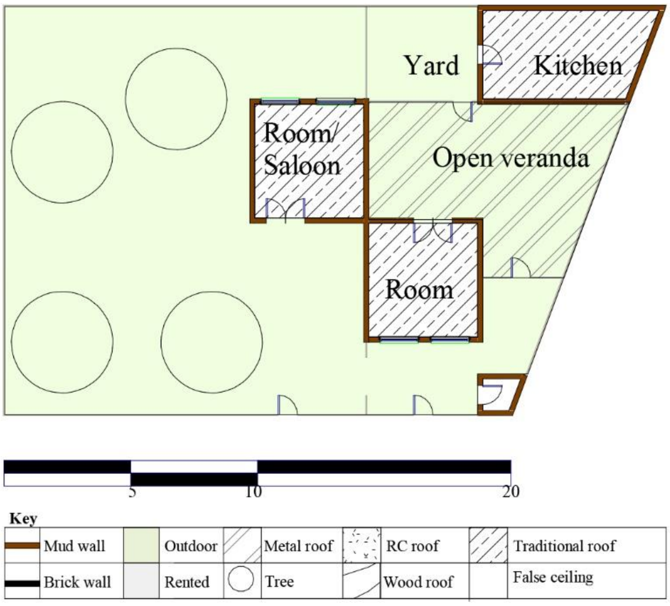


Figure 5.37 The evolution of T3

T3 shares similarities with both T1 and T2. It started as an institutional house like T2, but because the plot was larger and the government planning didn't limit them, they expanded the house drastically like in T1. The house's changes include living arrangement changes, the addition of spaces, the closing of verandas, material changes, sectioning for lodgers and the addition of evaporative coolers. Though there are two unconditioned spaces, the users leave the doors open from the conditioned rooms, which makes them 'semi-conditioned'. Sleeping outdoors stopped in Phase 3.

The first phase starts after the family built the house and moved in 1982, as shown in Figure 5.38. The family was a nuclear family with parents and four children. Their veranda had a corrugated iron roof and was closed off with mosquito mesh. The bedrooms had a thatch roof and mud walls. The house had a clear male and female zone with separate entrances. The room NE.BD was used for storage by the parents and the youngest daughter while the other room was for guests. This is typical in institutional houses and caused crowding issues as discussed in section 2.2.2. The house seems to be well ventilated, with each room having three windows and a door.

Figure 5.38 Building Phase 1 of T3



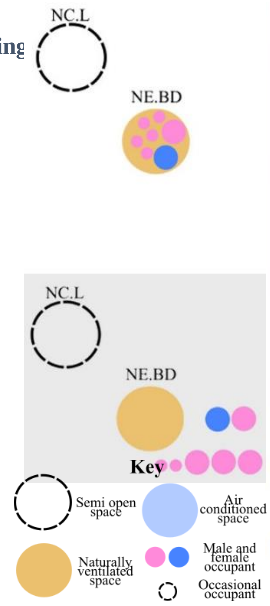


Figure 5.39 Occupant Phase 1 of T3

However, they still always opened the windows during power cuts and mornings only. Most of the time was spent in the yard, except during really hot periods. The family yard at the time had an extensive garden with lawn, flowers and trees. The moment the shade extended in the afternoon they took the mattresses out to sleep. They used to sleep in the yard, except during cold winter nights.

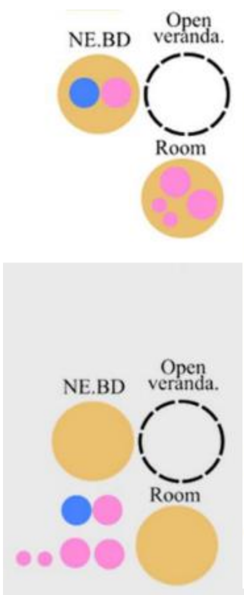


Figure 5.40 Occupant Phase 2 of T3

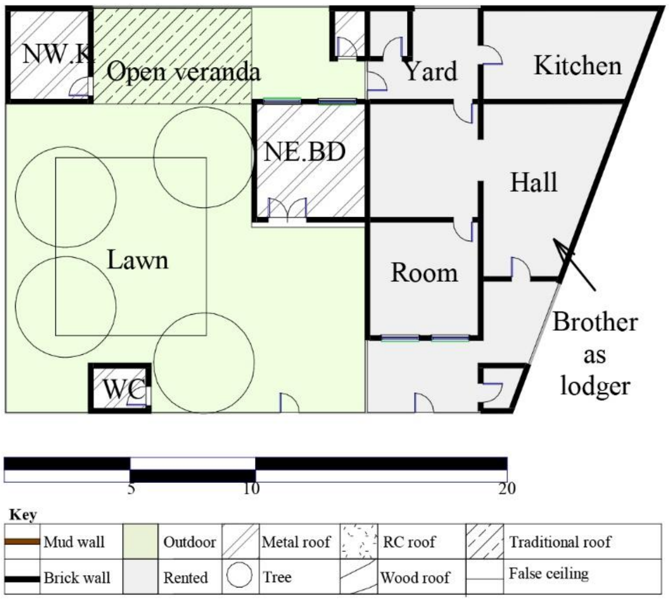


Figure 5.41 Building Phase 2 of T3

In 1991, the second phase started when the family had to move to a smaller left section of the house to allow more space for a brother to move in, as shown in Figure 5.41. The family had two parents and five children at this point. The brother (lodger) needed more internal space, so he removed the mosquito mesh and replaced it with brick walls to create two living rooms. The two families-maintained access to each other using the door on the north. The mud wall bedrooms were replaced with thick brick walls (40cm) and corrugated iron roofs. The owner said the rooms were hot, so he covered the iron roofs with bark and mud. A common practice to improve the thermal qualities of iron roofs where they are adopted as status symbols (Rapoport, 1969). To expand the small kitchen (NW.K), an open veranda was made using a thatch roof. The family still slept outdoors in the lawn.

Figure 5.42 Building Phase 3 of T3

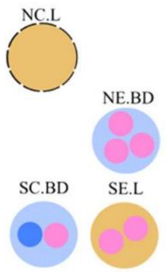
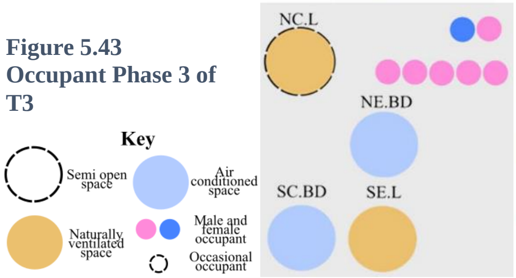
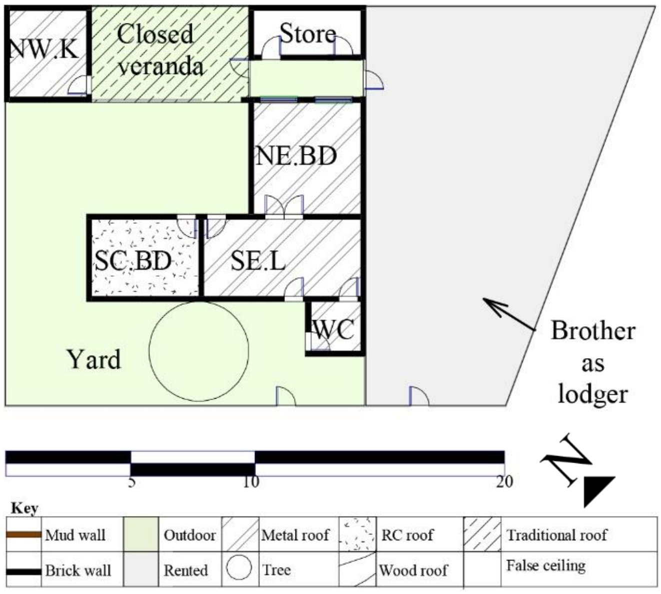


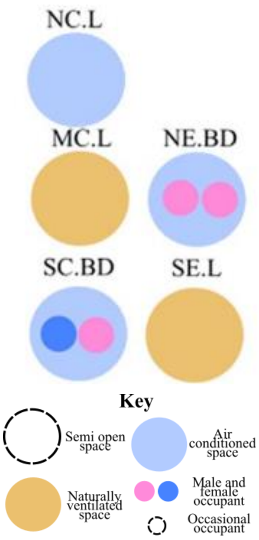
Figure 5.43 Occupant Phase 3 of T3





This third phase started when the father remarried in 2003, and the family transitioned from a growing family to an adult family. The owner turned the open kitchen veranda into a closed veranda by adding a brick wall but no doors or windows. He added a living room that also doubled as a bedroom. It had an iron roof. He also added a concrete-roofed master bedroom when he remarried. He stated that he would have preferred a modern house and wanted to add modern spaces one at a time slowly.The first evaporative cooler was installed for the master bedroom SC.BD. in the third phase in 2003. In 2006, another was added to the children's bedroom NE.BD. This addition marks the beginning of the mixed lifestyle with traditional and modern practices. The family continued to sleep outdoors when all five daughters were still home. They said that this time was their favourite time to socialize throughout the night.

Figure 5.44 A traditional wood window with a mosquito mesh at T3



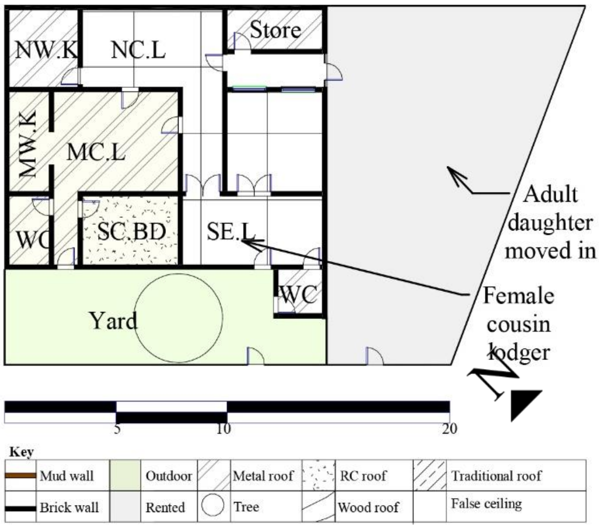


Figure 5.45 Building Phase 4 of T3

Figure 5.46 Occupant Phase 4 of T3

Phase 4 is the house in its current state after the family has transitioned from an adult family to a household. It is three distinct but related sections: the parent suite, the main family and the lodger/ daughter zone.

Usually, sons remain with their parents or daughters who are divorced, widowed, or their husbands are abroad. However, this case was different because all the daughters that got married moved out entirely, leaving an empty nest. This does not include the daughter who moved into the previously sectioned east side; only a female family lodger remains.

The closed veranda was turned into a hall. This move finally linked the entire house internally. However, the northern wall of this hall is directly connected with the neighbour's home without a setback, which was problematic, as mentioned in section 5.5.1. The master bedroom was turned into a separate suite with a kitchen, bathroom and living room; thus, the house functions as three different units. In 2015, false ceilings and ceramic tiles were added. The owner initially said he added the false ceiling for coolth, despite previously stating the metal/palm leaf combination was cool. When he mentioned adding the false ceiling the second time, he said it within the trend of 'adding tiles' and modernizing the house. The windows were replaced from wooden ones to metal as in T1. A similar trend is seen in Libya (Gabril, 2014). Figure 5.44 shows the original wooden windows with the mosquito mesh.

In Phase 4, The owner also added a moving evaporative cooler for the hall as there is no external wall to mount it on. This is also where the TV is located. After the daughters married and moved out, they stopped sleeping outdoors. They also said This happened around 2009 due to security concerns and violent robberies.

5.6.Conclusions

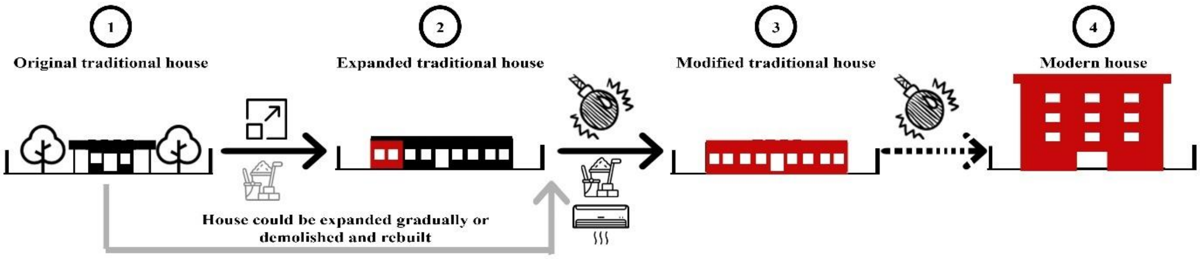


Figure 5.47 The evolution of the traditional Sudanese house

The case studies examined in this chapter have revealed that all three houses had undergone very similar patterns of change. This shared pattern has been illustrated in Figure 5.47. The families would start with a small home with a sizeable productive yard and semi-outdoor spaces. The natural materials would have had a high thermal mass that would have kept them cool during midday when it was hottest outside. The first change is usually triggered by socioeconomic pressures, namely the need for space and the need for income. These drivers would lead to an expansion that would decrease the amount of yard space available. This expansion would often encompass the verandas, which either become outdated or too troublesome for a modern lifestyle. The next stage is when the occupants decide to upgrade the building materials to keep up with the trends. This trend of demolishing mud houses and replacing them with brick, metal, or concrete is common in Khartoum, as mentioned in Chapter 4. These new building materials don’t perform as well as previous ones, so the occupants adapt. They try to add mud to the roof and false ceilings, and when that fails, they resort to mechanical solutions such as fans and evaporative coolers. Initially, these solutions are limited to the shared space as their lifestyle is still predominately social, and they sleep outdoors sometimes. However, security concerns and reduction in socialization reduce sleeping outdoors. This is compounded by increased privatization needs that increase time spent indoors in individual rooms. This pressure increases the number of airconditioned spaces, shove calls this ‘escalation’, where the pursuit of comfort becomes more resource intensive (Shove, 2003). Younger residents expressed less inclination to engage in energy conserving behaviour, most likely due to their decreased ownership. The impact of ownership can be seen in renters, as they consume 9% more than non-renters (Thorsrud, 2020) Also, households with a clear figure of authority consume less (Lutzeinhiser, 1993) Finally, even after the family members decrease, the number of conditioned spaces remains the same, likely resulting in the same consumption rate despite fewer occupants as fewer people share spaces.

When we look at this narrative, we can notice a few things. Firstly, the physical building changes are drastic, to the point they can be considered different typologies. From permeable shallow buildings with intermediate spaces to deep buildings completely cut off from the outdoors. The changes impact all six building layers: Site, structure, skin, services, space, and stuff (Brand,1994). We see a significant difference when we compare this narrative to changes happening in traditional courtyard houses that will be discussed later in this conclusion. The transformation of Sudanese houses involves frequent replacement rather than adaptation. Sudanese homes also lack the historical value of other middle eastern courtyards, which motivates owners to preserve them. This could be because Sudanese courtyards are single-story, unlike most other middle-eastern courtyards that were multi-story, built on limited plots and had structural walls linked to the spaces (Agha & Jm, 2018). The changes resemble more the behaviour of informal housing in Tunisia (Aksoylu, 1987), which starts as a single room occupied by a migrant, then expands before being demolished and replaced by multi-story apartment buildings housing an extended family. The house stages follow the family's increase in wealth and size.

Secondly, we can see that the building gradually loses the elements it needs to support adaptive behaviours. These include physical aspects such as the availability of large and safe outdoor spaces, thermal diversity in intermediate spaces, and high thermal mass that keeps cool midday. It also loses behavioural elements such as occupants willing to migrate, having time for adaptive behaviours, allocating spaces based on thermal function, not assigned to functions or people and lower comfort expectations. Vernacular architecture works using systems and cannot function with missing parts. Foruzanmehr notes that many of these components had other cultural functions; they were not purely sustainable. For example, the Sudanese yard facilitated socialization in the evenings and nights and losing that function impacted its use in T3. Finally, you can see that while the initial addition of the air conditioner is a reaction to the changes made to the building, the increasing adoption is more related to social change. This observation fits Brand's theory of 'flow' between the ongoing relationship between occupant and building; it is not a linear process but rather a two-sided interaction (Brand, 1994). The occupant's willingness to live a traditional lifestyle is impacted by modernisation, which entails weaker social ties, less security, and higher expectations for comfort, convenience and privacy. The air conditioner fulfils these needs; as Shove argues that comfort, convenience and cleanliness are the major motivations for using air-conditioners and electro-mechanical cooling systems (Shove, 2003). Thermal migration is typically considered uneconomical and inconvenient (Foruzanmehr, 2016). Foruzanmehr stated that the loss of this tool makes people more reliant on mechanical cooling and subsequently more vulnerable to climate change. This vulnerability is likely compounded by the fact that younger generations are already less 'resilient' than older generations as they grew up during an economic boom, compared to older ones that grew up during financial crises.

When we compare our observations to changes in other traditional houses in the general literature, we can see a few differences and similarities. In terms of lifestyle, in some cases, the occupants of traditional houses retained their adaptive behaviours in addition to air conditioning. In contrast, others became completely AC reliant like our case studies. An example of the former is a case in Iraq (Agha & Jm, 2018), the occupants changed space functions, added layers to the walls, covered the floor surfaces with temporary covers and added building services. They still lived an adaptive lifestyle with different behaviours in different seasons, such as spraying the yard, thermal migration, night cooling, using the badger, etc. Iranian traditional houses, however, found that the air conditioner replaced the need for adaptive behaviours, especially using the cool basements midday. In Libya, privacy and security changes in their community required occupants to create boundary walls, similar to T1 (Gabril, 2014). The houses, in this case, changed the space use to fit modern needs by converting the animal pen into a living room and abandoned sleeping on the roof. In India, Kotharkar noticed that traditional houses in rural settings retained their preference for open and semi-open spaces (Kotharkar & Deshpande, 2012). In semi-urban and urban areas, however, occupants in the exact same house type preferred private rooms due to fragmented neighbourhoods with less social life and security. Spaces in traditional houses in the urban setting also included the addition of furniture that made spaces lose their multi-function aspect. Houses were also divided into multi-family units. All similar to our case studies.

All the occupants have expressed their desire to build modern houses. This desire was driven by the need to expand into a limited space but maintain familial ties or keeping up with current trends. T1 and T3 attempted to do it gradually, creating a kaleidoscope of rooms with different materials. When moving forward in these buildings, the question is, should traditional houses be demolished and rebuilt or renovated to suit the users' modern needs? Estaji argues that to justify renovation, '*the value of the renovated building must be more than the sum of the land price and renovation costs. Otherwise, the renovation is not cost-effective, and the landlords will think about demolition* (Estaji, 2018, p. 25). Sudanese people historically preferred detached houses over apartments because of the yard and the community life in detached house neighbourhoods (Mohammed & Kurosawa, 2005); these incentives no longer exist in the three case studies. Which questions if that preference remains. The Sudanese house's habit of reinventing itself means that the modern house can be seen as an extension of the evolution of the traditional house, rather than a separate typology. Thus, looking at a sample of these modern houses is essential to see if they are better suited for a modern lifestyle.

Chapter 6 The hybrid villa, the next step in the evolution

6.1.Introduction

This chapter mirrors the themes and methodologies of chapter 5, but they are applied to case studies of two example of a modern housing typology, which will be referred as the hybrid villa. It also aims to understand how the interaction between building has occupants changed over time, however, the key difference is that these buildings were designed and used as modern buildings from the start. The chapter will first reflect on the adoption of modern indoor-based living in developing countries. It wil then look at the case studies by first introducing the surrounding area, then outlining the buildings overall evolution before detailing the phases the building went through.

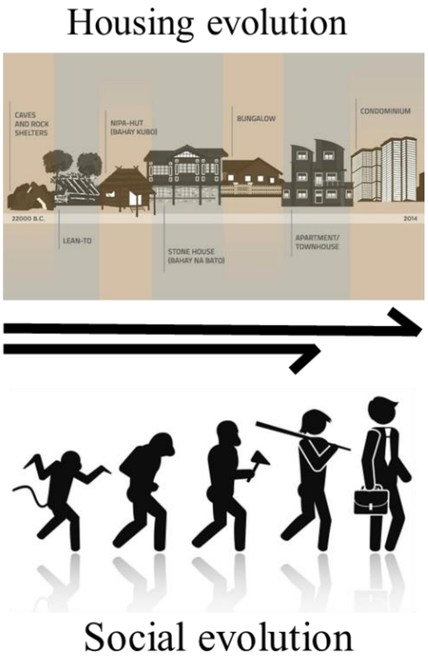


Figure 6.1 The evolutionary arms race between house's and their occupants

As do their houses, people constantly change in an cultural arms race illustrated in Figure 6.1. They adapt to each other as the circumstances around them change. Their relationship continuously flows rather than being linear or one directional (Brand, 1994). However, sometimes the pace of change between the two does not synchronise perfectly. Traditional houses in Africa endured hundreds of years of fine-tuning to meet the needs of their occupants. Then colonisation introduced modern houses that suited their white owners' lifestyle and view of comfort (Mclean & Hunt, 1908). This created a typology that was completely detached from its local cultural and climatic context.

Another example of this imposition is how European houses built originally for nuclear families do not suit the extended family structure of the native Māori and Pacific peoples (Gray & Mcintosh, 2011). McLean designed houses for British officers without semblance to the local architecture in Khartoum. Colonisers often also imported their views on Urban planning (Leichenko & Solecki, 2005). In the British case, they favoured wide straight streets to maximise ventilation, which they believed was paramount for thermal comfort in the tropics (Mclean & Hunt, 1908). This impacted the house design, as previously mentioned in section 2.3. The colonial government also used architecture to segregate the population. They imposed material regulations that meant only wealthy foreigners could build modern brick buildings in the city centre, while the local mud houses were limited to the city fringes. This polarisation emphasised the modern house as an imposed foreign entity that had to be 'localised' after independence. Several modern African projects have failed because they did not do this correctly (Ikudayisi & Odeyale, 2021).

Muller said*: 'architects have apparently thought the external form of the old-fashioned rural houses was the most essential element of the African tradition to be maintained. African citizens, on the contrary, attach great value to living in a modern-looking house which expresses their social status and aspirations. At the same time, they want a house that has an internal arrangement of rooms which allows them to live according to their own norms of behaviour.'* (Muller, 1984, pg.365)

Even outside the context of colonisation, in developing countries, housing types evolved from traditional to modern faster than the lifestyle change of their population, which made these houses a replacement rather than an adaptation (Mirmoghtadaee, 2009). In Mirmoghtadaee's study of the evolution of the Iranian house, he highlighted that the medium-rise outward-looking house was the next step from the courtyard house (Figure 6.2), like the evolution of the Sudanese house mentioned in the previous chapter. These houses did not fulfil the users' need for privacy, which was previously fulfilled by the courtyard's introverted nature (Abdelsalam, 2017). To cope, conservative Iranians covered windows with thick curtains and used the balconies as storage (Mirmoghtadaee, 2009). The population pressure then introduced the high-rise apartment building, which had similar problems to its predecessor.

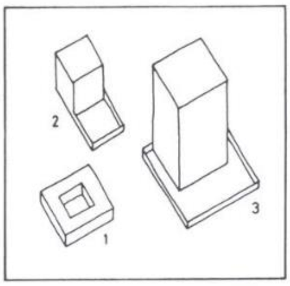


Figure 10. The Changing Pattern of the Building Form,
From (1) an Inward-looking, Low-rise Courtyard House to
(2) an Outward-looking, Medium-rise House with a Courtyard, to
(3) High-rise Apartment Buildings
Source: Madanipour (1998)

Figure 6.2 The evolution of the iranian house typology. Source: (Mirmoghtadaee, 2009)

A contrasting example to the Iranian apartments is the traditional houses in the red sea style of the Hijaz and Suakin (Figure 6.3), which are among the few traditional Arab houses without courtyards. As mentioned previously, when change is slow, traditional architecture copes. In these highly dense multistorey buildings, the Mashrabya, decorated meshes, provided privacy for balconies (Eyüce, 2012). These balconies were an extension of the home that was often used.

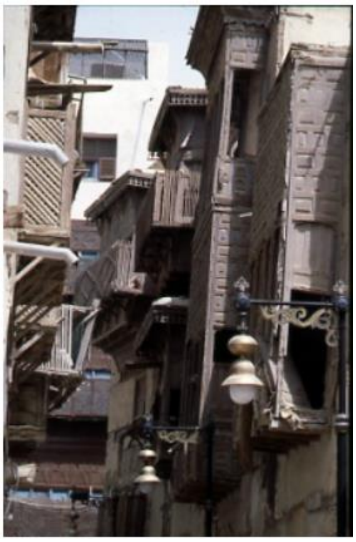


Figure 6.3 Hijazi style buildings with mashrabiya balconies (Eyuce,2012)

Another example of the abrupt adoption of modern buildings is in Saeed's description of the Western villa in Saudi Arabia; he said: *'The villa is characterised by relatively thin external walls from reinforced concrete, large glazed openings to the outside facing different directions and exposed open spaces which neither suit the climatic conditions nor the social requirements of a Muslim society* (Saeed, 1989, p. 50) The 'Europeanization' of these Arab countries (Saeed, 1989) impacted Sudan as expats imported their western culture to Sudan around the 1970s-1980s (Mohammed & Kurosawa, 2005). You can see this in Karmal's similar description of how the traditional building evolved into the modern one in Sudan. He defined it *as 'the replacement of the verandah by the enclosed living hall, the tendency towards more compact forms, the inclusion of the kitchen and bathroom with the main building and the excessive use of concrete, glass and air-conditioning'* (A. Osman, 2016).

The opposite situation is when the occupants change faster than the building. In New Zealand, houses built for the 1950s traditional nuclear family were unhealthy for the current ones. In the past, the wife would stay at home, opening the windows and drying the laundry outside, while modern working couples kept the house sealed and empty most of the day (Gray & Mcintosh, 2011).

Figure 6.4 represents the different possibilities discussed previously. The starting point is traditional houses suited to their occupants' lifestyles. Case two shows that if the building changes to a modern one, it could suit the occupants if modified successfully. The cases mentioned in Iran, Saudi Arabia and Africa represent the result of adopting modern buildings as they are, which is the third case. The fourth case happened in the traditional Sudanese house, where the occupants changed faster than the building. Finally, the fifth scenario is if the occupants and buildings are modernised equally. So, where does the modern house in Sudan currently fit? Though it may have initially clashed with the occupants' traditional life, it's possible that as occupants have now changed, it may be acceptable.

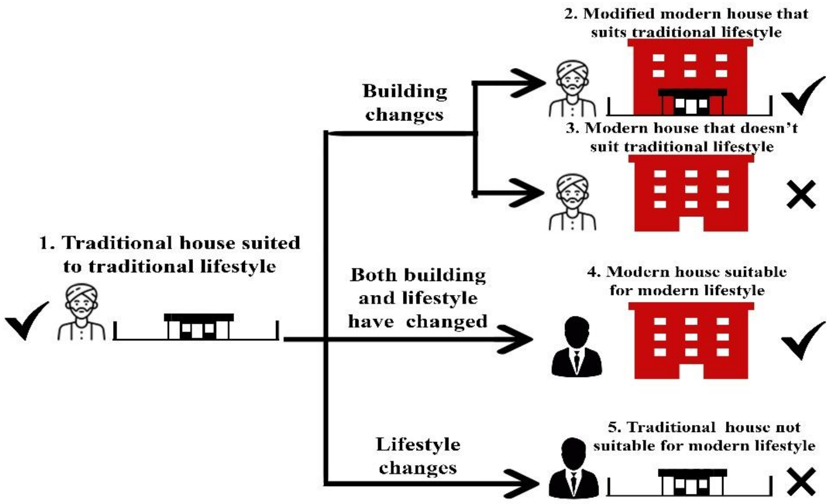


Figure 6.4 Possible evolutions of building and occupants

6.2. Selection criteria

Osman and Suliman (1996) described the 'contemporary house', which can be considered a precursor to the Mediterranean-style villa. It shared the same layout where everything was under one roof. They differ because the villa is usually multistorey, necessitating a concrete frame to support this vertical expansion. Whereas contemporary houses could be constructed of different materials as they could be single storey or multistorey. The second difference is the larger glazed openings and exposed spaces due to the lack of verandas and shading. These characteristics were considered when choosing the sample buildings. Figure 6.6 shows the location of M1 and M2, while Table 6.1 gives an overview of their characteristics. These selected buildings are currently hybrid villas, a typology that has replaced the villa as the most popular modern type in the past 20 years (Hamid, 2021). The distinction is important because commercial properties are usually rentals where profit is the key design goal, not the occupants' comfort. These apartments provide access to a private yard, a key reason why Sudanese people rejected apartments (Mohammed & Kurosawa, 2005).

This typology is the type the users in traditional houses aspired to as it fulfils the social need for multi-nuclear families to live together in a limited space. It also meets the financial requirements such as high land prices, efficient space use and lower costs compared to apartment blocks (Hamid, 2021). Furthermore, the occupants' complete control over adjusting their environment is crucial in this study. Though this study focuses on the hybrid villa, many findings can be applied to similarly constructed contemporary buildings. Houses in Khartoum were preferred for ease of access and to ensure the urban context is similar to sampled courtyard houses for comparison. The houses can be modified or left in their original floor plan.

The sample requirements for occupants and equipment are the same as those for courtyard houses in section 5.2. To summarise, the house must have an AC, preferably a mix of evaporative coolers and split units or window units. The owners must be the original occupants, and both extended and nuclear families are accepted. The only difference is that it is preferred that they are expats from Saudi Arabia. Saudi Arabia has the largest expat Sudanese community, and these expats imported the western villa. Also, The predominant type of occupants in concrete houses are expats or people who sold their expensive houses in central areas and moved to the periphery (Eltayeb, 2003), Which makes them more representative as occupants of the sample. The occupants are acquaintances of the author.

The two chosen samples represent relatively well-designed villas with some shading and reasonable glazed areas. However, many villas in Khartoum feature glazed curtain walls like the one shown in Figure 6.5 . These have not been included in the study because their owners are likely upper-class and it is evident that with that high level of glazing, they cannot be sustained without air conditioning.

Figure 6.5 An upper-class residential villa in Khartoum-Omdurman. Source: Murtada Muaaz company website

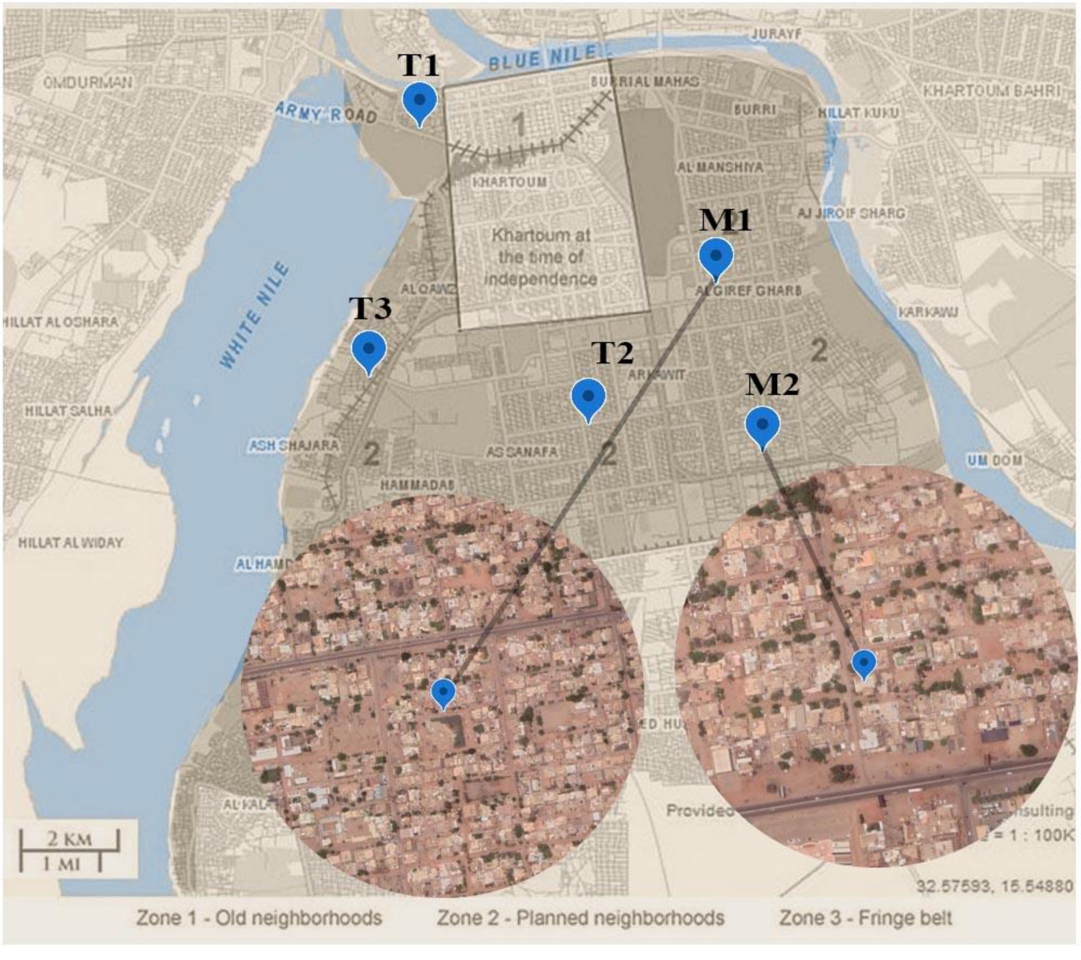
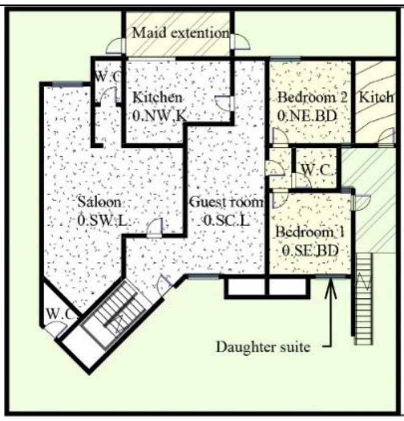
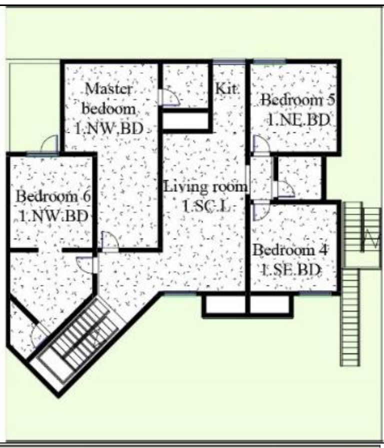
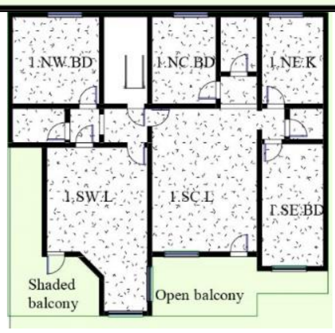


Figure 6.6 Locations of M1 and M2 within Khartoum

Table 6.1 Overview of the characteristics of M1 and M2

<table>
<tr><td colspan="2"></td><td>M1</td><td>M2</td></tr>
<tr><td colspan="2">Ground</td><td></td><td></td></tr>
<tr><td colspan="2">First</td><td></td><td></td></tr>
<tr><td colspan="2">Second</td><td></td><td></td></tr>
<tr><td colspan="2">Built in</td><td>1980s</td><td>1990s</td></tr>
<tr><td colspan="2">Occupants</td><td>6+5</td><td>6</td></tr>
<tr><td rowspan="3">Area</td><td>Built</td><td>222 m²</td><td>182 m²</td></tr>
<tr><td>Unconditioned</td><td>85 m²</td><td>29 m²</td></tr>
<tr><td>Conditioned</td><td>145 m²</td><td>81 m²</td></tr>
<tr><td colspan="2">No. of rooms</td><td>9+4</td><td>5+5</td></tr>
<tr><td colspan="2">Yard surface</td><td>Concrete tiles</td><td>Ceramic tiles</td></tr>
</table>

6.3. Case study 4 – M1

Overview

Figure 6.8 Altaif neighbourhood

Figure 6.7 Photos of the buildings surrounding M2

Al-Taif was agricultural land until the owners built their house in the 1980s. The occupants said they were among the first homes built in the area. After the centre of Khartoum shifted, the area became mainly inhabited by wealthy expats, several of whom came together from Saudi Arabia and chose to live near each other. The neighbourhood is planned with regular wide streets and several open spaces, as shown in Figure 6.8. It is adjacent to a highly commercialised neighbourhood called Al-Riyad, which created a demand for housing nearby. Many new buildings in Al-Taif are now rental apartments. The remaining buildings are all villas or multistorey apartment buildings with three or more floors, as shown in Figure 6.7.

MT was built in the 1980s. The three-story house was originally designed as a 2-story villa and later converted into a hybrid villa. The family is a returning expat family composed of two parents and five children.

Figure 6.9 Photo of M1

Before living in this house, the parents originally came from Omdurman from a wealthy family. Their original homes had ACs since the 1960s; however, it was only in the living room, and the family lived a very traditional lifestyle. Conformity in their neighbourhood was paramount, so even wealthier families like them made sure their house was the same as everyone else. This could be the reason they maintained their traditional lifestyle despite affording to install AC units in all the spaces. The older occupant reflected that returning expats introduced this culture of 'showing off' from wealthier Arab countries. Her comments echo the characteristics of shifting from a collectivist community to individualism, as will be further discussed in section 6.1: Individualist cultures promote standing out rather than fitting in.

The family moved to the UK in the 1960s and then to Saudi Arabia within the same decade. Their house was constructed during their time abroad and rented for ten years. The house had window units installed initially. In Saudi Arabia, they lived in a cold mountainous region with a heating season but not a cooling one. This could explain why comfort standards in this house are higher than in the other case study buildings.

The evolution of M1

Figure 6.10 The evolution of M1

Figure 6.10 shows the evolution of M1. The main changes were adding a floor, expanding internal spaces into balconies and the yard, subdividing the house into independent units and upgrading the air conditioners. The building is on a 370 sqm plot, and the built area is 222 sqm. The footprint has remained around 60% for the past 40 years.

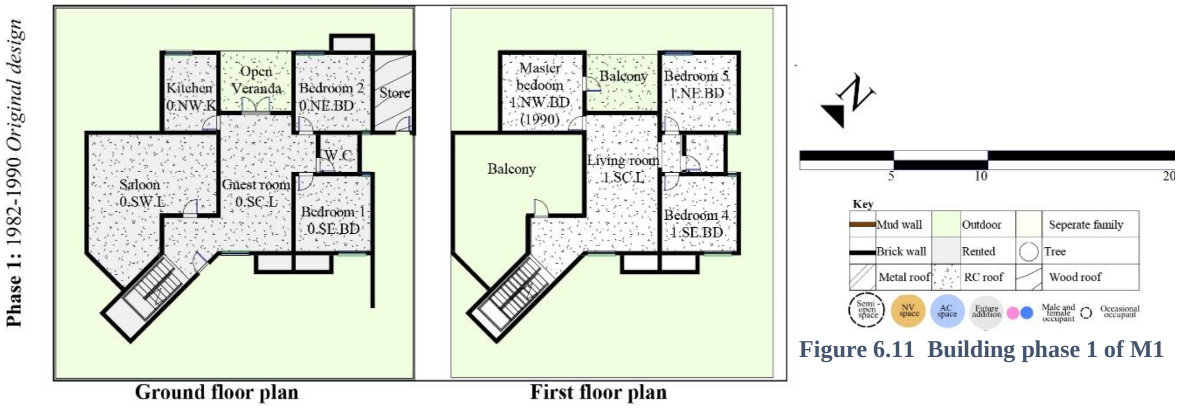
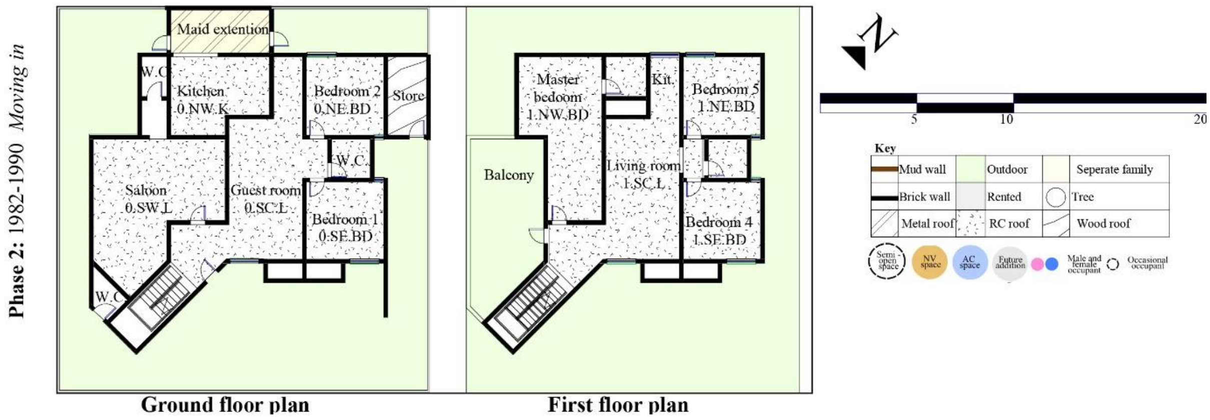


Figure 6.11 Building phase 1 of M1

The first phase started before the family moved in when the house was rented. The building was a two-storey villa. A master bedroom was added in 1990 to increase the number of rooms in the house. An established architect designed the house. Despite being among the first houses in the neighbourhood, the architect knew most of the neighbours would build multistorey buildings. So, he provided privacy to the family's courtyard using the building and a free wall. He also included a large, sheltered balcony for sleeping and verandas in the design. The architect also used built-in wardrobes around the exterior walls, which act as a thermal buffer zone. However, besides the security grill, he did not provide any shading to the southern windows. The stairs were tilted to give privacy to the balcony from the street and privacy to the yard from the western neighbour. The renter/lodger installed window units as they were from a wealthy background; they were also related to the family.



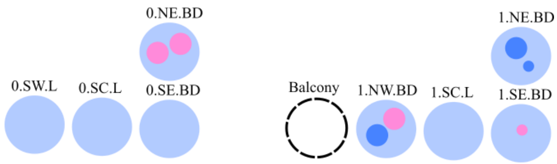


Figure 6.12 Phase 2 in the building M1

The family moved in during the second phase after they returned from abroad and adjusted the house to suit their needs. The occupants consisted of the parents, five children and a maid. Most of the changes were related to expanding the interior spaces, such as the kitchen and master bedroom. They also added a kitchenette and ensuite to the master. These expansions caused the loss of the ground-floor veranda and first-floor balcony. When asked why the occupants reported that they were not used anyway, they said they were too hot compared to the conditioned outdoors. The family lived predominately indoors, as they had in Saudi Arabia, despite the parents living a traditional outdoor-based life before their expatriate. This highlights that merely adding a veranda or balcony without considering how the family uses the house creates redundant space that will inevitably be expanded into. On both the ground and first floor, this meant converting the veranda into kitchen spaces that benefit them more. They also said the upper balcony was too small to function properly for sitting or sleeping. To separate the maids from the main household, they were given a metal roof kitchen extension and a separate bathroom. Metal was used because it is illegal to build in the setback. Therefore, people use temporary materials in case they are forced to remove them. A similar observation was seen in H3 in the author's previous study (Elsherif et al., 2020).

They installed evaporative coolers instead of the 'noisy' window-type air conditioners. They used to sleep in the large balcony occasionally as the architects' design meant it was private and sheltered by the stairs.

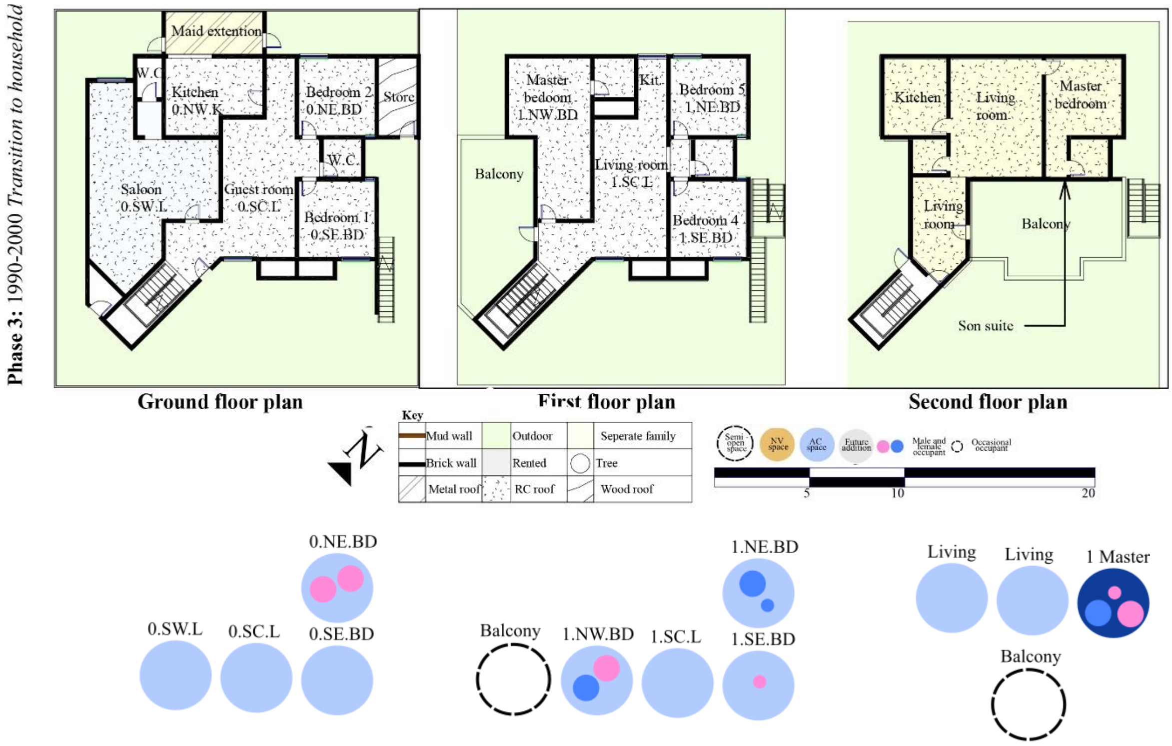


Figure 6.13 Phase 3 in the building M1

The third phase is where the family transitions from an adult family phase to a household phase. One of the children married and built an extra floor during this period. This change transformed the house from a villa to a multi-apartment building. The building was not designed to accommodate an additional floor, so they used a lightweight structure with thin concrete and brick walls. They had installed a more efficient window unit in the bedroom and an evaporative cooler in the living room. Occupants in Khartoum prioritise night-time comfort (Merghani & Hall, 2001) and install better AC there (Elsherif et al., 2020). Another reason they do this is that the living rooms are usually large and would be costly to condition with a refrigerant AC. An additional exterior open metal staircase was added to act as a separate entrance .but is rarely used due to its inconvenience and exposure to outdoor elements. Had it been originally part of the design, it could have been designed more securely.

Figure 6.14 Phase 4 of the building M1, the crossed blue spaces are where the AC doesn't work

Phase 4 is the house in its current state. During this phase, a second child married and moved to the ground floor. The main changes focused on accommodating her in a separate-but-attached configuration to the main house. The store was turned into a kitchen to ensure independence from the main household. The open entryway linking the east side to the west wing on the ground floor was closed off with a door for privacy. A closed metal veranda was used to safely connect Bedroom 1 to the kitchen and add a separate entrance from the street. A split unit was installed in Bedroom 1. As the outdoor unit of the split unit is within a narrow alleyway closed by the veranda, the temperature rises there, which reduces its efficiency. The daughter and her family moved out in 2018. When they're abroad, the space is used for guests, but when they come on visits, it becomes their apartment again.

The saloon was extended for aesthetic purposes. The feeling of a larger space reflects wealth and status. The aspirations of the traditional houses to become modern also stems from this desire to reflect wealth, or at the least, that you are on par with all the other houses. According to an elderly resident in M1, this desire to flaunt wealth was not the norm in the past; it's a construct imported from Arab countries. She mentioned that everyone built the same house type, even if they were wealthier, to maintain conformity. Wealth was only expressed through frequent banquets to share that wealth with the community. This is another reflection of the transition of the Sudanese people from a community-based society to an individual-focused one. *'Individualist cultures prioritise independence and uniqueness, whereas collectivist cultures emphasise family ties and fitting in'* (Santos et al., 2017).

An additional bedroom was added on the first floor, replacing the last balcony. The large main balcony was initially used to sleep in as intended in phases two and three. The family had to stop using it because their neighbour installed illegal west-facing windows, which impacted their privacy. The neighbour installed those illegal windows because he had divided the floor into more flats for rent, creating rooms with only a west-facing exterior wall. According to the owner, the new floor also blocked airflow to the balcony. This further reinforces that, as mentioned in section 4.2.5, commercialism encourages breaking the law and poor design decisions that impact the user and their neighbours. It also highlights that in the context of M1, the moment the outdoor space became redundant for whatever reason, it was replaced by internal spaces. The need for extra space is not as pressing here as in traditional houses.

Most evaporative coolers in the house stopped working (Figure 6.14), and the constant maintenance became troublesome. Therefore they installed two split units in the new bedroom 1.NW.BD and the master bedroom 1.NC.BD and used them alternatively to save energy. They also added a moveable evaporative cooler in the kitchen for the maids. So overall, the number of conditioned rooms has remained the same, but the consumption has increased to the AC type change. The occupants use the two spaces with split units most of the time. This decision left most of the house unused, an empty nest like T3, which masks how much the house is genuinely consuming if consumption per meter calculations included the unused space

The residents on the last floor still have beds on the roof, which they use during power cuts. They also added another bedroom as their family grew and will likely expand further into the existing balcony as their space needs increase.

6.4.Case study 5 – M2

Overview

Figure 6.15 A map showing Al-Mamoura neighbourhood

Figure 6.16 Images of buildings in Al-mamoura neighbourhood. Taken by the author

Al-Mamoura neighbourhood was farmland up until the 1990s, as shown in the urbanisation plan in section 4.2.1. As Khartoum's centre shifted from Al-Souq Al-Arabi to the nearby airport area, it became a sought-after neighbourhood by expats and the upper class. Most of the buildings have two or more stories. They are either villas or multistorey apartment buildings, as shown in Figure 6.16. The main streets are surrounded by a strip of commercial buildings, as shown in Figure 6.15. Al-Mamoura is a planned upper-middle-class neighbourhood with open spaces, and the roads are straight and wide.

M2 was built in the 1990s as a 2-story villa made of RC floors and brick walls. The enclosed balconies shade the western and southern facades, while neighbours shade the eastern and northern ones. The architect designed the villa to be easily converted into apartments if needed.

Figure 6.17 A photo of M2

The expat family comprises two parents and their remaining four adult children. The other two adult children are married and visit every weekend. The father originally comes from an affluent house in Khartoum, where he grew up with evaporative coolers, window units and fans. They also slept indoors. The mother lived in a rural town with a courtyard house and slept outside, especially when the power was cut. After they got married, they moved to Saudi Arabia (KSA) and remained there for 35 years. They lived in a modern villa with window units. Living in KSA, they did not like the apartment life and wanted more space in the rooms and areas to socialise. The impact of this desire can be seen in the spacious living rooms they designed in their home. Their goal was to build a house similar to other homes in Khartoum, which reflects the need for conformity in Sudanese culture. Though a yard was initially planned, they cancelled it because friends told them it could cause leaks around the house. The construction commenced between 1997-2003.

The evolution of M2

Figure 6.18 The evolution of M2

The family started gradually moving in during 2017. They installed evaporative coolers in every space except the kitchen. Their choice was driven by the energy consumption rates of ACs. They rarely open the windows because of the odour coming from burning trash.

In 2020, They started changing the first floor into two rented flats while they moved downstairs. The only change in the floor plan is that 0.SE.L became the master bedroom. This change effectively turns the building from a private villa into a multistorey apartment building, as they plan two additional floors for their children. Their children, however, want to immigrate as soon as possible. Their plans include closing off the balconies because only the father uses them, and they 'bring in the dust' and hot air and lack privacy. These balconies, however, provide shade for the building's south and west façade, as shown in Figure 6.19. Occupants also shared this complaint in traditional houses, highlighting the impact of a modern lifestyle in reducing outdoor usage in both typologies.

Figure 6.19 Balconies in M2 providing shade for the southern façade

They rarely use the yard unless there is a power cut or on rare occasions when the weather is good, and a guest comes over. They only open the windows in the morning. At night they only open the window if there is a power cut, and they cannot stay outside due to mosquitos.

6.5.Conclusion

The first noticeable difference between the evolution of traditional and modern buildings is that the modern buildings underwent fewer physical changes to adapt to the user's socioeconomic changes. Houses M1 and M2 are as old as T2 and T3, respectively, which means they both had the same time to adjust to the user's needs. The vertical element in the modern houses helped create a more substantial separation between family units. The 'nuclear family' based lifestyle is more evident in M1 than in the other extended households, T2 and T3. For example, the occupants in the traditional houses share all their meals together, but the occupants in M1 cook and eat in separate zones. Separating the kitchen is vital to independence in extended households (Klocker & Gibson, 2013). The occupants in M1 and M2 can also leave and enter the house from separate entrances. M1 and M2 needed to convert into hybrid villas; however, this decision was a design consideration in M2 and allowed it to be done with minimal changes, simply adding a couple of walls. Additionally, M1 risks structural damage from the unplanned floor. As mentioned previously, designing for flexibility and adaptability enables changes to be made without the house losing value, thus ensuring its longevity (Estaji, 2018).

The need for suitable outdoor space is a problem in M1 and M2, despite the architects' efforts to provide privacy and adequate space in both cases. The outward nature of balconies makes them exposed by default, which makes them, in the Sudanese context, redundant areas that are rarely used. Outdoor spaces must be designed to provide shelter from dust and privacy. They must also be adequate for performing a function like socialisation or sleeping away from the hot walls, a problem in small courtyards (Merghani & Hall, 2001). The Hijazi architecture includes high walls on the roof space as a proposed solution. Provision should also be made if the owners decide to close it into an internal space that would not impact other spaces' quality. For example, a Serbian study analysed traditional houses with verandas and proposed ways for the houses to be extended into the veranda while still maintaining energy performance and lighting standard.

Chapter 7 Social change and energy consumption

7.1. Introduction

Previous chapters have retraced the adaptation of Sudanese houses in response to changes in the occupants' needs, looking at the micro and macro scales. Chapter 2 examined the historic evolution of the Sudanese house due to socioeconomic change, which was followed in chapter 4 by a study of the current conditions. Chapter 5 then explored this evolution at the scale of individual buildings, focusing on three case studies. This section was then followed by an analysis of two hybrid villas in chapter 6, which represented example of the most recent stage in the evolution of the Sudanese home. The concern of this chapter is to explore in more depth the current way occupants use buildings in order to find solutions that suit the family’s lifestyle and thus, are more likely to be easily implemented. It was mentioned in the introduction of Chapter 6, that houses in New Zealand were no longer healthy because people shifted towards a working parents model. Therefore, any proposed solution that still requires the occupants to be available at home during the day would be impractical.

This chapter will revisit the five case studies from the user-behaviour perspective. It starts by identifying the general patterns of occupant behaviour through qualitative methods, which will be further investigated using the quantitative data from the monitoring conducted. The AC use patterns will then be explored to see when the AC is used the most, by whom and why. This information will be contextualised within the general occupation patterns explored in the previous section. For example, a reduced AC use in a certain period in a house might be explained by the occupants routine, like having a midday siesta. The following section looks at the link between AC use and outdoor temperatures to see if AC use changes with the months or is more habit driven. Finally, the impact of the usage pattern on energy consumption is identified for each case . The third house, T3, was omitted as monitoring could not be conducted for whole period. Also, several monitors failed throughout the monitoring period, so there are gaps in the data that will be highlighted whenever necessary.

Energy Consumption and user behaviour

Occupant behaviour is the most significant predictor of energy consumed by the AC for cooling, followed by the number of rooms conditioned (Yun & Steemers, 2011), which necessitates mapping these patterns to include them in proposed solutions and building energy models. The difference between the modelled and actual performance is primarily attributed to occupant behaviour. In several experiments in the UAE, predicted energy savings from building upgrades were less than actual savings due to the users' environmental awareness and behaviour (Giusti & Almoosawi, 2017). The performance gap can underestimate 30-100% of a building's actual consumption (Al Amoodi & Azar, 2018). Occupant behaviour in the project BedZed led to a variation of energy consumption patterns of up to twenty folds within the same housing design (Samuel & Dye, 2015).

Secondly, this variation in user patterns affects overall consumption as well as how loads are distributed across the day (Lutzeinhiser, 1993). During the covid pandemic, the loss of the morning commute shifted the morning peak to later in the day as people adjusted their routines (Users TCP and IEA, 2020). Reducing peak demand can reduce the need for large electric plants because the loads are more evenly distributed. As the peak load in Sudan is higher than the capacity of the grid, power cuts are scheduled to balance this (Ghandour, 2016). Finally, when the building's schedule is optimised to the occupants' usage patterns, reductions of up to 39% can be achieved (Al Amoodi & Azar, 2018).

Occupant behaviour, especially concerning cooling, is impacted by two predominant factors: socioeconomic drivers and thermal preferences (Tam et al., 2018). It has been shown in the previous chapters that Sudan has undergone considerable social changes, which have had an impact on user behaviour and, consequently, energy consumption. Underlying these changes is a fundamental shift from a collectivist towards individualist outlook. *'The collectivist ideology emphasises groups, other people, and community, while individualism is based on concerns for oneself and one's immediate family.'*(Kim Rand-Hendriksen et al., 2012, pg54) Increased individualism is a global phenomenon (Kim Rand-Hendriksen et al., 2012; Santos et al., 2017). It is linked to improved socioeconomic conditions and feelings of safety due to a reduction in disease and natural disasters (Santos et al., 2017). A better quality of life means priorities shift from survival and safety to health and comfort (Nicol et al., 2020). This transition aligns with Maslow's hierarchy of needs and it has energy consumption implications as people who perceive their comfort level as highly important are less likely to engage in energy-conserving behaviours (Lutzeinhiser, 1993). Another impact of individualism is that it promotes living in single households rather than extended families (Santos et al., 2017). As shown in section 2.2, this results in an increase in resource consumption. Individualism also encourages people to have their own designated space, which will likely hinder thermal migration opportunities as fewer spaces become public. Another significant social change is an increase in the time spent indoors. The more hours users spend indoors, the higher the consumption (Blasco Lucas et al., 2001). For example, high thermal mass buildings are uncomfortable at night in hot climates as they release their stored energy. This problem makes them suitable for offices but challenging for homes. People adapted to this problem by sleeping outdoors, but today spending those hours indoors by cooling the building with air conditioners increases consumption (Merghani & Hall, 2001). Especially because night comfort is prioritised (Merghani & Hall, 2001), these behavioural changes requires the building to be comfortable throughout day and night, which limits architectural solutions that often work at different times.

7.2. User space use patterns

To understand when occupants used different spaces, interviews and a behaviour log were employed to track the user patterns. The log was done on weekdays and weekends to capture both patterns. The day has been divided into four periods. The morning starts when the family members have left for work/school, which is usually the quietest period of the day. Most jobs in the private sector begin at 7:00-7:30 and end at 15:00-16:00, while schools also start at 7:00 but end earlier at 14:00. This is why the 'afternoon' period starts after they arrive. The evening starts after office hours, and the commute home till bedtime, so from 17:00-21:59.

Table 7.1 Usage pattern types observed in the case study buildings

Bedroom					Living room				
P	**Morning** 7:00-13:59	**Afternoon** 14:00-16:59	**Evenings** 17:00-21:59	**Night** 22:00-6:59		**Morning** 7:00-13:59	**Afternoon** 14:00-16:59	**Evenings** 17:00-21:59	**Night** 22:00-6:59
1					**1**				
1a		Siesta			**2**				
2					**3**				
2a		Siesta			**4**				
3					**5**				
4									
4a									

Table 7.1 shows the usage patterns found in the case study buildings for bedrooms and living rooms. The research identified four main patterns for using the bedroom (Table 7.1), starting from just using the bedroom to sleep (Pattern 1) to using it all day and night (Pattern 4). Patterns' two and three extend the night-time use into the evening and school hours, respectively. In addition to these key patterns, there were variations when a siesta was added, or the occupant left during evenings to socialise. Similarly, living room use was graded from not being used at all (Pattern 1) to use all day but not at night (Pattern 5). It could also be used only at night (Pattern 2), only during the evenings (Pattern 3) or both (Pattern 4).

This section will detail how these patterns manifest in each case study. They help create a framework to understand the reasoning behind the AC use patterns mapped by the data loggers in section 7.3. For example, a logger can show that the AC was turned on midday, but the interviews are needed to understand that this is when the occupants come home specifically to take a siesta. Data loggers also do not account for the occupancy when the AC is turned off, and they also do not reflect the use of individual users as several occupants share most rooms. Therefore, combining qualitative and quantitative methods helps triangulate the data and overcome gaps.

A case study of behaviour in household T1

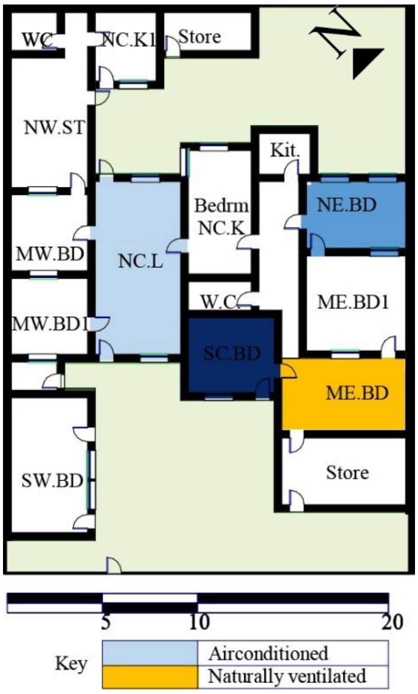


Figure 7.1 Plan of house T1

T1 is an extended household with occupants of different ages and genders who are the remaining members from different nuclear families. Specifically, there is two sisters with some of their adult children, their adult brother and two remaining children of a deceased sister. This fractured structure has caused them to function more as two units, a female and male one, rather than separate nuclear families as previously. The females share their meals in the kitchen while the males each eat in their individual bedrooms. The living room (NC.L) is sparingly used, except by a male Millennial who sleeps in it as his AC is defunct. All four bedroom usage patterns were observed in this house, which can be seen in

Table 7.2. The male millennial works all day and only comes to his bedroom to sleep as he is a freelancer. The two female Gen X spend their evenings and nights in their rooms. The unemployed female also has a siesta around 14:00-15:00, the rest of the day is spend doing the chores around the house as she is the 'mother figure'. The three daughters spend all their time in their rooms after coming home from school, two are students and the third is a young teacher. Finally, the unemployed male spends all his day in his room and only leaves in the evenings to socialise. When he does work, he comes to have a siesta in the afternoon before leaving in the evening. The differing annual schedules for the students and employees result in them being on vacation at different times. This results in an almost year-round consumption at all hours of the day.

During weekends, other family members visit. Observations showed that the younger visitors use the unofficial living room NE.BD while the adults usually congregate in the female adult's bedroom MW.BD. Dinner is served in the kitchen, where they all eat together. The living room is only used for guests, especially after a TV was added in the male's room SW.BD and the family bedroom SC.BD. Though the bedroom MW.BD is not technically conditioned; the unemployed female used the living room NC.L's AC with the door open. It was observed that the house is always occupied. A relative drops off her children at the house every day; the residents alternate staying at home to babysit. Also, for security reasons, they rarely leave the house empty. This impacts energy consumption because it means there are no periods where it is more acceptable to be uncomfortable, and the house is in a constant state of consumption. They do not use the yard at all, due to the heat, the mosquitos and the lack of time. Even during power cuts, it is too 'stuffy', they prefer the battery. They only use it for special occasions like weddings.

Table 7.2 General usage patterns in the household T1

P	Morning 7:00-13:59	Afternoon 14:00-16:59	Evenings 17:00-21:59	Night 22:00-6:59	User	State
Bedrooms						
1					M Millennial	FT employee
2					F Gen x	FT employee
2a		siesta			F Gen x	Unemployed
3					F Gen Z F Gen Z F Millennial	Student Student FT (teacher)
4a					M Gen x	Unemployed
Living room (NC.L)						
1					All occupants	
2					M Millennial	FT employee

A case study of behaviour in household T2

The household in T2, like T1, is an extended family comprised of the remaining members of different nuclear families. They include two adult sisters with some of their adult children and their elderly uncle. All the occupants have a job or go to university; 7:30 is the latest when the last person leaves the house. They are also divided into male and female groups. The grandfather and a male grandchild stay in the Saloon, which serves as a living room reserved for males and their guests. When there are any male lodgers, as is the case here, they usually sleep in the Saloon. The grandfather works daily, while the grandchild

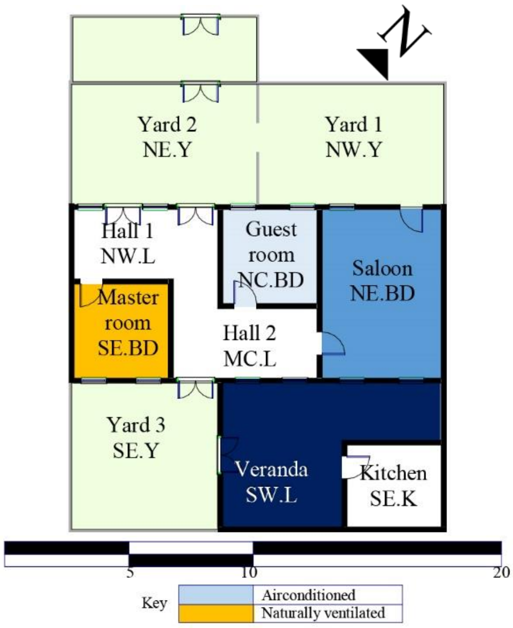


Figure 7.2 Plan of the house T2

works two days and stays home the other days. They use the AC predominantly when they have a siesta after work in the afternoons but sleep without it. The females come home around 4 pm, eat together in the veranda SW.L, and spend their evenings there. The female Gen X does not have a designated sleep space; she sleeps in one of the halls. A second female Gen X resident occasionally comes when the house is empty to guard it, she sleeps in the air-conditioned bedroom NC.BD with the female student Gen Z. This female student is the only one who spends all day in the room and rarely leaves it as she prefers the cool. The other female student sleeps in the unconditioned bedroom SE.BD with another occasional visitor as they do not mind the hotter temperatures. As an extended family household, the number of people in the house changes daily, with only five fixed residents and two frequent visitors. In this house, people have less distinct designated areas; people often switch their sleeping places within their male and female zone respectively. They do not use the yard unless there is a power cut or a large gathering.

Table 7.3 General usage patterns in the household T2

P	Morning 7:00-13:59	Afternoon 14:00-16:59	Evenings 17:00-21:59	Night 22:00-6:59	User	State
Bedrooms						
1					F Gen X	FT employee
2a		Siesta			M Boomer	FT employee
3					F Gen Z F Gen Z	Student Student
4					M millennial	PT employee
Living room (SW.L)						
4					All females	

A case study of behaviour in household T3

House T3 is occupied by a retired couple, their adult daughter and a female lodger. During the course of the study the daughter married and moved out, which meant she could not provide monthly reports from the data loggers. The usage pattern was estimated using information collected from a log filled by the users over two days and through semi-structured interviews completed before the daughter moved out in 2021.

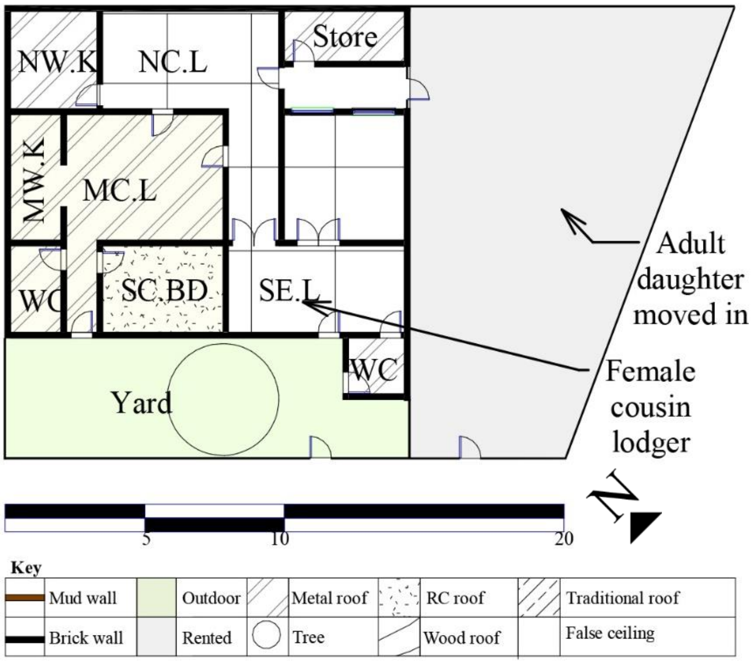


Figure 7.3 Plan of the house T3

In the morning, the daughter leaves for work and returns in the evening when she turns the AC in her bedroom NE.BD on medium till the next day. She and the lodger use the northern hall and the living room alternatively during the evening without a specific pattern. They use the bedroom AC to cool it when using the southern living room. Her sisters visit on weekends, and that's when they use both living rooms more extensively, probably meaning that both ACs get turned on simultaneously rather than alternatively. The living room NC.L serves like the veranda in T2-SW.L in that it is a space near the kitchen but has a TV so they can cook and watch TV concurrently. The other living room SE.L is a guest reception.

The family functions as two separate units; each one eats separately. The father stays in his bedroom SW.BD most of the day along with the stepmom, who only leaves to use their section's living room during chores. This extensive use of the room could be because the metal roof in MC.L gets very hot during the day and his RC bedroom has an evaporative cooler that he uses sparingly. He believed keeping the AC on all the time is unhealthy and wasteful. Most likely, older models are widely believed to cause joint problems from the higher humidity. So, he only turns it on low before bed to cool the room before opening the windows. Older ACs (evaporative coolers) were less efficient, and you would have to stay right in front of the AC, but newer ones cool the whole room with fewer humidity issues, according to the younger occupant.

Table 7.4 Usage patterns in T3

P	Morning 7:00-13:59	Afternoon 14:00-16:59	Evenings 17:00-21:59	Night 22:00-6:59	User	State
Bedrooms						
2					F Millennial	FT employee
3					F Gen Z	Student
4					M Boomer F Boomer	Unemployed Unemployed
Living room (NC.L)						
1					Weekdays	
5					Weekends	

A case study of behaviour in household M1

Household M1 is composed of three separate units. On the ground floor are three maids. The first floor has retired parents and an adult daughter. The second floor houses a married son and his family. During office hours, the parents would spend time in the upstairs living room while the daughter went to work. In the afternoon, the father would nap in the master bedroom while the mother would still remain in the living room. The maids spent most of their time in the kitchen. The daughter would come home around 6 pm and spend all her evening in bedroom 1.NW.BD during the summer and her own bedroom 1.SE.BD during the winter. The father sometimes goes on social errands during the day or in the late evenings. At night, the three family members sleep in bedroom 1.NW.BD while the maids slept in the Kitchen extension initially. During this period, they had a lodger in 0.SE.BD; after the lodger moved out, the maids slept in this room to access the AC, which broke down and was replaced with a portable evaporative cooler. The living room and kitchen were the most used

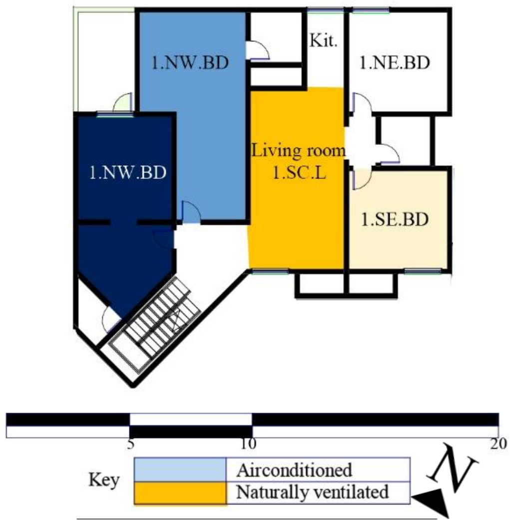


Figure 7.4 plan of the house M1

spaces during the day, and it was the shared bedroom 1.NW.BD and kitchen during late evenings and nights. That means only three spaces in the house are regularly used. On April 2021, the occupants installed an AC in bedroom 1-NC.BD to extend its use during the day, but still slept in bedroom 1.NW.BD to conserve energy.

Table 7.5 Usage patterns for M1

P	Morning 7:00-13:59	Afternoon 14:00-16:59	Evenings 17:00-21:59	Night 22:00-6:59	User	State
Bedrooms						
1a		siesta			M Boomer F Boomer	Unemployed Unemployed
2					F Millennial	FT employee
2a		siesta			F Gen X F Millennial F Millennial	Au pair Au pair Au pair
Living room (NC.L)						
					F Millennial	FT employee
5					M Boomer F Boomer	Unemployed Unemployed

Table 7.6 confirms the patterns recorded in the interview with the bedroom NC.BD being used mainly during the day, and the bedroom NW.BD mainly in the evening and night, as the probability of the AC turning on, was higher. The values were obtained by calculating the duration the AC was on during May 2021, when they first installed the AC, compared to the total number of hours in the month.

	NW.BD	NC.BD
00:00	76	44
01:00	83	47
02:00	85	42
03:00	84	41
04:00	84	40
05:00	85	35
06:00	79	44
07:00	68	56
08:00	59	59
09:00	42	65
10:00	30	63
11:00	36	63
12:00	38	60
13:00	36	60
14:00	35	62
15:00	38	66
16:00	46	72
17:00	51	57
18:00	63	52
19:00	67	41
20:00	67	36
21:00	65	33
22:00	66	37
23:00	69	39

Table 7.6 The probability of space occupancy in MT in May 2021

A case study of behaviour in household M2

M2 has a nuclear family composed of two retired parents, an adult daughter and son, and two school age sons. The general pattern is that during office hours, the mother is around the house doing chores, mainly in the kitchen and the living room. The father has a routine where he spends his early mornings in the yard and then time in the balcony before having a nap during noon. In the afternoon, the family watch tv and eat lunch in the living room. After which the boys retire to their room and only one of them plays on the PlayStation in the living room during late evenings. The parents and their daughter sometimes stay to chat before bedtime. At night, everyone sleeps in their bedrooms, the eldest son sleeps upstairs after the move. What is interesting is how the daughter spends the most time with the parents, while the sons, especially the oldest one leads an independent life. All the spaces in the house are equally used with bedrooms predominately at night and the living room most of the day. However, the boys' bedrooms are used day and night, another difference between the usage patterns of the older and younger occupants. Table **7.7** shows the usage pattern for the occupants in M2.

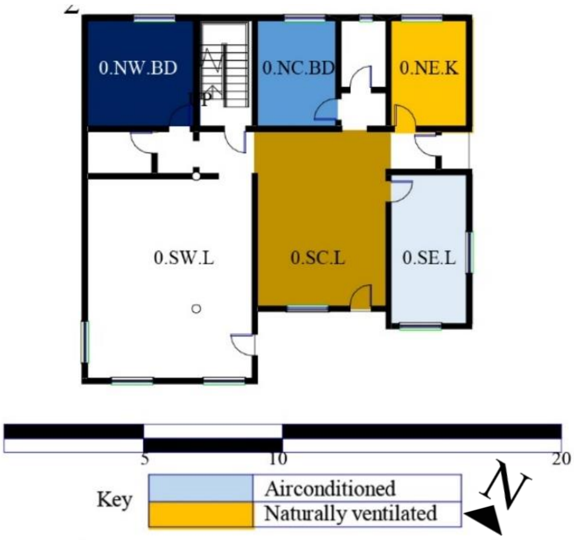


Figure 7.5 Plan of M2

Table 7.7 Usage patterns in M2

P	**Morning 7:00-13:59**	**Afternoon 14:00-16:59**	**Evenings 17:00-21:59**	**Night 22:00-6:59**	**User**	**State**
Bedrooms						
1					M Millennial	FT employee
1a		siesta			F boomer M boomer	Unemployed Unemployed
2					F Millennial	FT employee
3					M Gen Z M Gen Z	Student Student
Living room (NC.L)						
2					F Millennial M Gen Z	FT employee Student
4					F boomer M boomer	Unemployed Unemployed

As mentioned in section 2.2.4, rooms did not have a designated function like a bedroom or living room. In the past, the 'room' was only used for the midday siesta. However, in these case studies, rooms are used extensively daily and at night. Only three individuals used the bedroom solely for sleeping at night. Retirees used it for siestas as well. Employed occupants and students used the bedrooms as soon as they got home, while a few occupants rarely left their rooms entirely. Living rooms were used the most extensively by retired parents. Employed occupants sometimes used them in the evenings, but many rarely used them at all. Only one occupant reported using the private outdoors spaces regularly.

7.3. AC use patterns: a comparative study

The previous section showed how the users described their usual space use patterns. This section focuses on their actual AC use, as logged by the data loggers. Though the study aimed to track the usage of each occupant to cross-reference it with the patterns revealed previously, this could not be reliably mapped, especially in the extended households. This is because the users shared most bedrooms and frequently changed sleeping arrangements throughout the year. Therefore, some speculation will be needed to link the two data sets from the interviews and the loggers.

Average daily AC use patterns during the summer

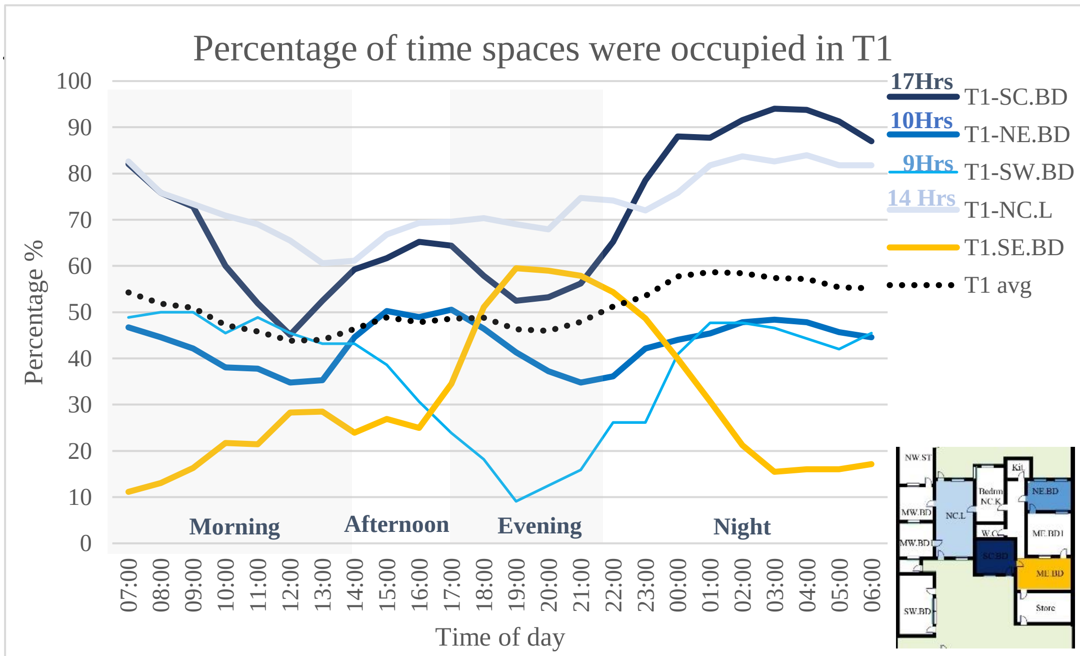


Figure 7.6 The usage patterns of spaces in T1 during May, June and July of 2021 Note: numbers on the key are the average number of hours the AC was on in the space.

Figure 7.6 shows the different AC use patterns as recorded by the data loggers in T1. The space SE.BD was unconditioned, which is why a carbon data logger was used to estimate usage patterns. Firstly, we noticed that the bedroom ACs were used more frequently in the morning than the interviews' suggested, up to 70% at 9:00. This discrepancy is explained by the fact that the occupants were often on vacation due to the COVID-19 pandemic and political instability mentioned previously. An increase in energy usage was also observed in the case study T3, when the female occupant had to work from home due to Covid in 2020. Both these instances highlight the potential increased residential energy usage to events that impact the country and lead to the increased time spent at home.

During the afternoon, the two bedrooms NE.BD and SC.BD experience a first AC use peak when the students come home, followed by a drop in the evening as they spend time in SE.BD socialising or doing chores in the kitchen. Around 4 pm, the female Gen X arrives from work and turns off the AC in the bedroom SC.BD, as it irritates her allergies. Which means the room is occupied during that period despite the AC use drop on the graph. The younger occupants sharing the room use other spaces during this time. This shows how sharing a room by occupants with different schedules and preferences impacts the room's AC consumption.

During the evening, the male occupant in bedroom SW.BD leaves, causing a significant drop in AC use. The AC within the living room (NC.L) was extensively used daily and at night, which contradicts the user's statement that they do not use the living room often. It can be explained by the fact the family had a newborn in May 2021, and these are guest visit times.

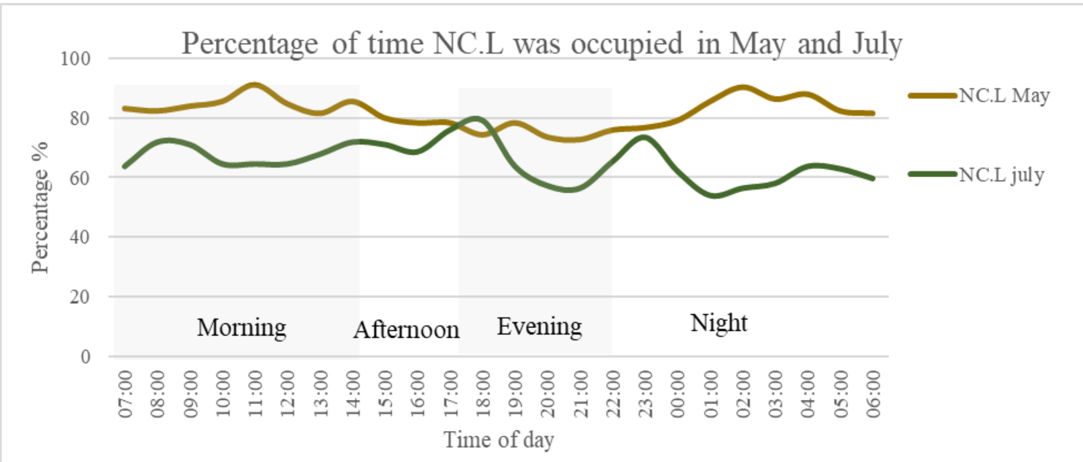


Figure 7.7 A comparison between the consumption of NC.L during and after the newborn event in May

To measure this impact, the assessment was done with the living room NC.L and was divided into May/June and July usage. Despite an almost 20% drop in use, as shown in Figure 7.7, it was still high in July. The AC in the living room is also used to cool adjacent spaces. The male occupant used it at night, which is not typical. This is probably why the users still thought they did not use the AC often. However, atypical situations are common in Sudan due to frequent social events like births, weddings and Ramadan. The average daily use varied from 9 to 17 hours, as shown in Figure 7.6.

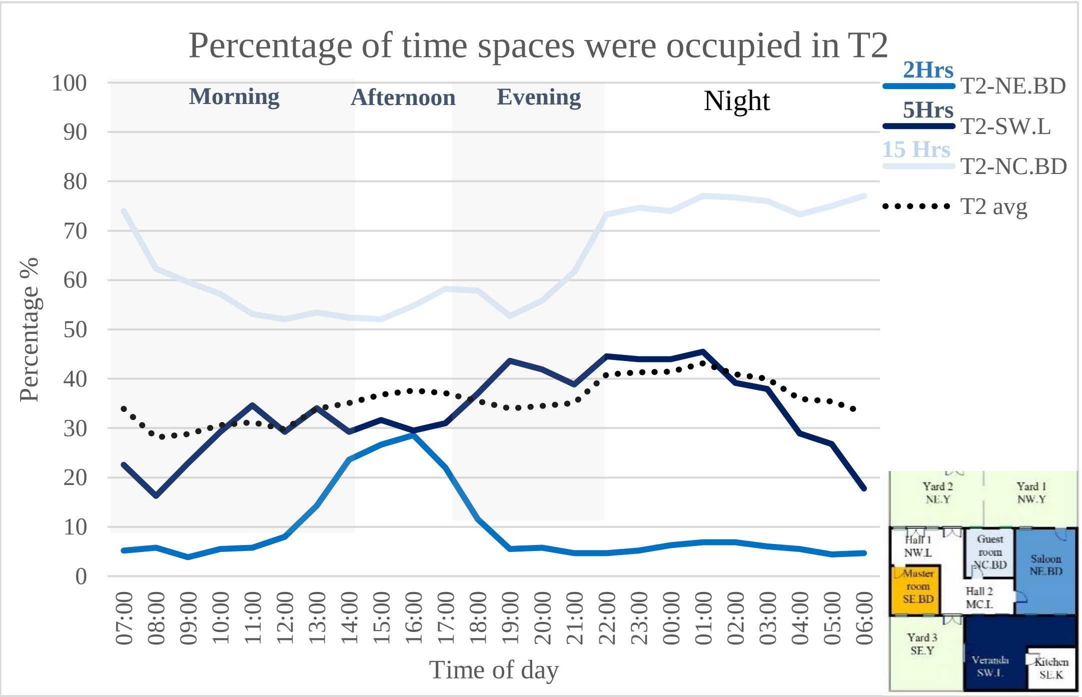


Figure 7.8 The usage patterns of spaces in T2 during May, June and July of 2021 Note: numbers on the key are the average number of hours the AC was on in the space

Figure 7.8 shows when the ACs were turned on in T2. In bedroom NE.BD, despite occupying the room all day, the AC is only turned on in the afternoons for the males' siesta. In bedroom NC.BD, the use is high all day as the student stayed at home, but it peaks at night when the door is left open to cool the entire house until 7:00 the following day. A habit the occupants started when this was the only AC in the house. The veranda AC in SW.L was turned on more at 19:00 and left as they spent late nights watching TV. The morning and afternoon use is because someone is always home doing chores in the nearby kitchen. The AC in bedroom NC.BD was used for 15 hours daily, compared to just 2 hours in the Saloon NE.BD and 5 hours in the veranda SW.L.

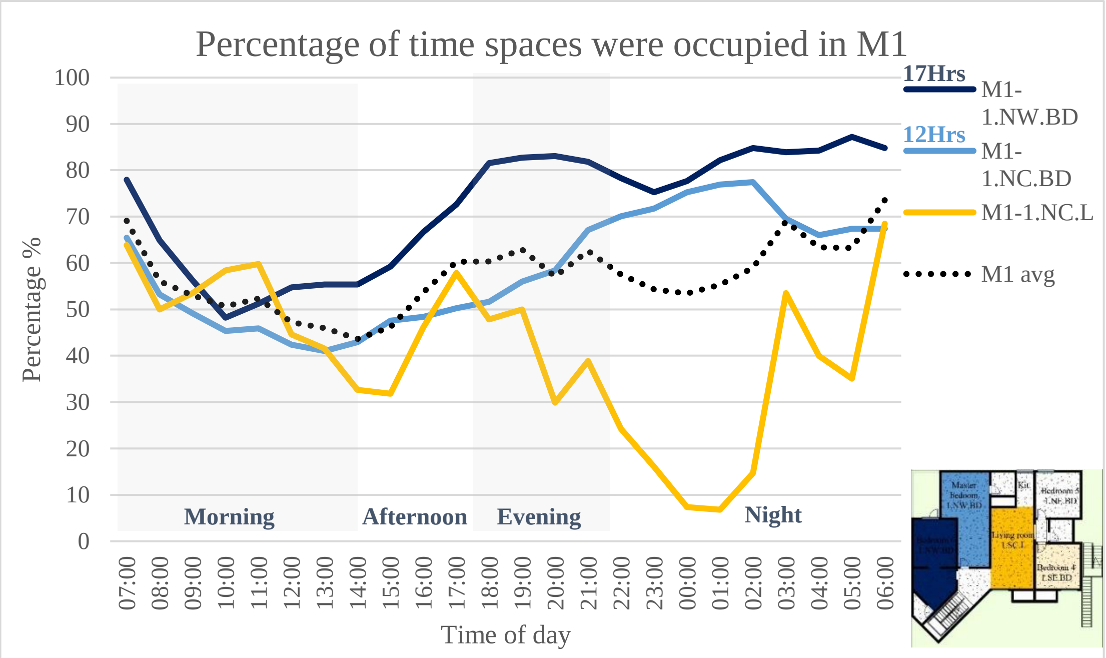


Figure 7.9 The usage patterns of spaces in M1 during May, June and July of 2021. Note: numbers on the key are the average number of hours the AC was on in the space

As mentioned in section 6.3, M1 initially used the bedrooms NC.BD during the day and NW.BD at night to conserve energy. Figure 7.9 shows that in the subsequent year during the same period, NC.BD started to function like the other bedroom NW.BD, just at a lower rate. This means the family no longer shares the room to conserve energy. The father returned to sleeping in his own room NC.BD. The increased AC use in NW.BD started earlier in the evening when the female returned from work. The living room (NC.L) was only used intermittently at night (2:00-4:00), mornings (5:00-10:00) and evenings (15:00-19:00). As mentioned, the retired occupants used the living room throughout the day except during their afternoon siesta. The night peak is when the father goes to pray at the mosque before dawn. The AC was on for 12-17 hours per day. Even its lowest usage rate in the mornings was above 40%.

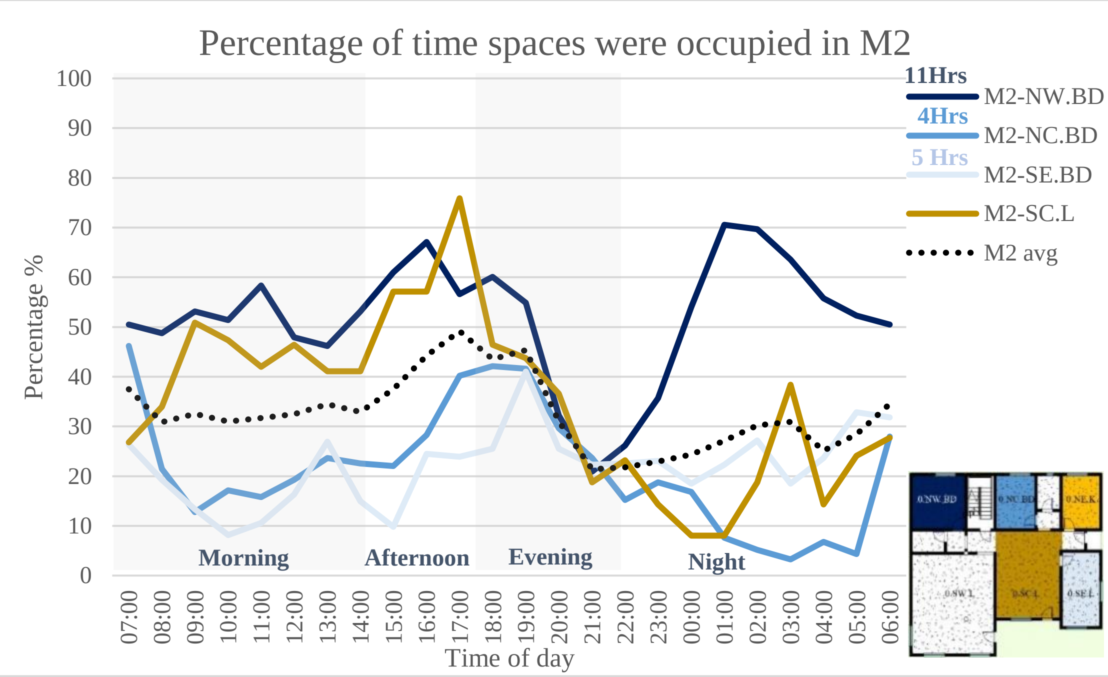


Figure 7.10 The usage patterns of spaces in M2 during May, June and July of 2021 Note: numbers on the key are the average number of hours the AC was on in the space

Figure 7.10 shows that in the boy's bedroom NW.BD, the usage rate was consistent all day with a sharp drop in the evenings, most likely spent outdoors or in the living room. The AC logger failed from 28/5-26/9, which means an accurate summer usage is not available, but only their use for May. The use in the living room SC.L increased gradually and peaked in the late afternoons (17:00) after everyone returned from work or school for dinner. The female Millennial used her AC (NC.BD) in the early mornings and evenings after returning from work, but not at night. She only used it to cool the room on hot nights before turning it off rather than keep it on all night. The AC in the parent's bedroom SE.BD shows high use at night, during the siesta at noon and 19:00 after dinner. AC use was 4-5 hours in the bedrooms SE.BD and NC.BD but increased to 11 hours in the bedroom NW.BD.

When we compare all four usage patterns, shown in Table 7.8, we notice significant variations in how the AC is used. With bedrooms, the most common pattern was having the least AC use in the morning, then gradually increasing until it reaches peak use at night. This is interesting because temperatures are typically cooler at night, yet this has not deterred AC use. This is likely because sleep comfort is prioritised and because the night time has the highest occupation rate of the day. Its also possible that the thermal lag increases night discomfort, this will be further explored in chapter 8.

A third of the bedrooms experienced a drop in AC use in the evening as users visited friends, did chores or socialised in the living room. In M2, their peak living room use was in the late afternoon, so they retired earlier to their bedrooms in the evening rather than at night. The occupant in the bedroom NC.BD was the only one that rarely used her AC at night. Living rooms generally peaked in the evenings, except for NC.L, which behaved like a bedroom. Living rooms were used more in the mornings when the house had retirees.

Table 7.8 Comparison of AC usage in the 4 case study buildings

House	Space		Morning 7:00-13:59	Afternoon 14:00-16:59	Evenings 17:00-21:59	Night 22:00-6:59
T1	Bedrooms	SC.BD				
		NE.BD				
		SW.BD				
		SE.BD				
	Living	NC.L				
T2	Bedrooms	NE.BD				
		NC.BD				
	Living	SW.L				
M1	Bedrooms	NW.BD				
		NC.BD				
	Living	NC.L				
M2	Bedrooms	NW.BD				
		NC.BD				
		SE.BD				
	Living	SC.L				
Key		AC usually turned on	AC sometimes turned on	AC rarely turned on	Likely occupied	Unlikely occupied

AC use throughout the year

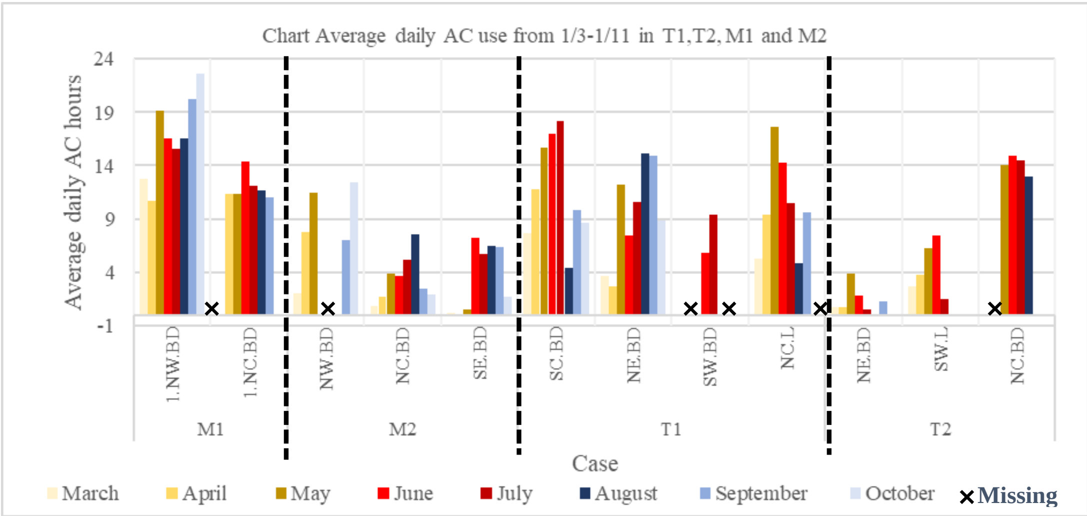


Figure 7.11 Average hours the AC was turned on in T1, T2, T3, M1 and M2

This section explores the AC use throughout the cooling season. Temperatures increase in May and peak in June before dropping in August and rising for a second peak in September. Therefore, the AC use rates should reflect that, if outdoor temperatures mainly influenced them. Figure 7.11 shows the average daily AC hours in the 4 case study buildings; each one shows a different pattern. M1 was the only one who used the AC extensively throughout the entire eight months at a similar rate. The use is habit driven in this house as users tend to have fixed routines. They set it at a high set point of 27°C to offset the extensive use. The other three houses varied their use with the increasing temperatures with T1 using it almost as much as M1, which indicates a possible thermal discomfort problem. T2 and M2 limited both the peak usage hours and the use months to just 4-5 months. As chapter 8 will further explore, M2 is thermally comfortable but T2 is not. This means that the reduced use in T2 is rather because the occupants leave the house for extended periods (section 7.1) and the older occupants tightly monitor AC use (section 5.4) for economic reasons.

Due to the prohibitive cost of fully air conditioning the entire building, all the buildings in this study are mixed-mode buildings with a combination of conditioned and unconditioned spaces. None of the spaces was kept within a stable range through constant conditioning like middle-class American homes. This AC use study reveals that even their conditioned pockets are intermittently conditioned throughout the day and the cooling season.

7.4. Annual electric consumption patterns

The usage patterns identified in the previous sections show extensive AC use that impacts energy consumption; this section aims to quantify that impact. kWh plugs were connected to most evaporative coolers, and an electric meter was installed for one of the two split units. Some ACs could not be tracked because they would require changing the wiring. Instead, the usage patterns for these ACs were recorded using Hoboware motor loggers that recorded the pump's vibrations. An estimate of their electric use was plotted based on the consumption rate of other similar ACs in the same building.

Meters in Sudan are prepaid, which makes tracking consumption hard; therefore, the electric purchases were recorded (Appendix A.8). The electric purchases do not reflect the actual overall consumption but help estimate it. The occupants in this study tended to underestimate their actual energy consumption. This discrepancy could be because the prepaid system does not allow them to track their consumption. They often 'top up' their electricity at the end of the month when prices are usually higher. This problem could lead to overconsumption and reduces the incentive to make changes. In houses with 'master meters', where residents pay their electricity with the rent, they consumed 35% more because they were unaware of their consumption (Lutzeinhiser, 1993). Even when occupants had monthly access to meters, upgrading to smart meters that provided live feedback lead to a reduction of 2.2% in electricity and 1.5% on gas (Users TCP and IEA, 2020).

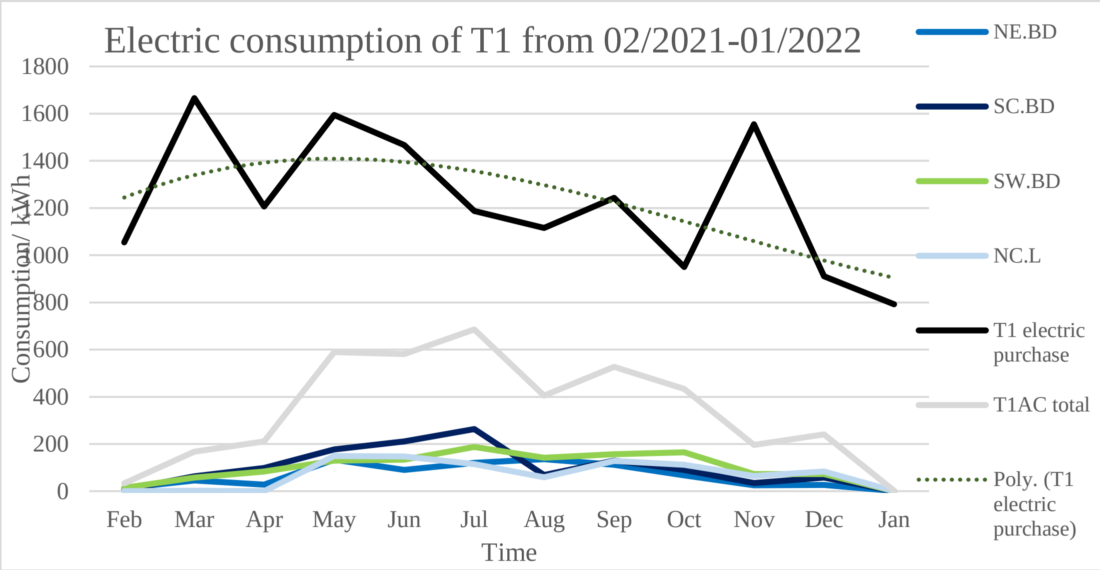


Figure 7.12 Electric consumption of the ACs in T1 from 02/2021-01/2022

Figure 7.12 shows the consumption of individual ACs in T1, their collective consumption and the electric purchases made by the family throughout the year. A portable evaporative cooler used in May and part of June is unaccounted for as it did not have a meter. Overall there were two peaks in July and September, which follows the outdoor temperature patterns. However, the bedroom SW.BD (green line) maintained a more consistent consumption rate throughout the AC use season. It could be theorised that the male occupant in SW.BD uses the AC as a habit rather than a response to how hot it is. The electricity purchases fluctuated wildly throughout the AC usage season. How much the AC consumed from the overall electric purchase varied. It started at 12.5% in March, reaching 50% in July. According to the motor data loggers, the ACs were turned on average for 10 hours in NE.BD, 14 hours in NC.L and 17 hours in SC.BD. This consumption rate was calculated during the peak consumption period from May to July. SW.BD was only monitored for two weeks before the logger malfunction. Although the two-week sample suggests the AC was used for 9 hours per day on average, the kWh meters show both SC.BD and SW. BD's AC was turned on 73% of the time. The power cuts occurred over 10.8% of the time. This calculation means that, during the summer, the users only willingly turned off the AC in these two spaces 16% of the time. In all the spaces, the AC was turned on for more than 24 hours straight in several instances. The occupant estimated they pay 15,000-20,0000 pounds per month, yet during the month the occupant made that statement, they had purchased 60,000 pounds of electricity. However, this was not paid at once but as three instalments of 20,000.

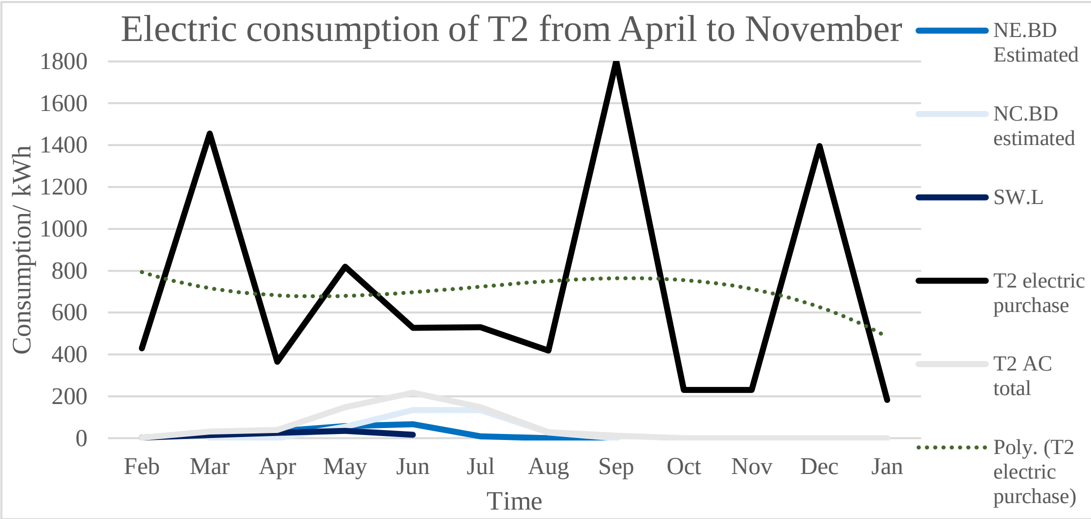


Figure 7.13 Electric consumption of the ACs in T2 from 02/2021-01/2022

In T2, only one evaporative cooler was fitted with a kWh logger, and the others are estimated based on the usage hours logged by the motor loggers. T2 shows a more conservative consumption pattern. The occupants only used the AC during the peak between April to August. Nevertheless, their electric purchase was high, reaching 1800 kWh in September. Over the year, the average purchase was 660 kWh, which is higher than the occupant's estimate of 200 kWh. The thermal implications of limiting the AC use will be explored in the chapter 8. The power cuts lasted 22.4% of the time, twice as many power cuts as T1.

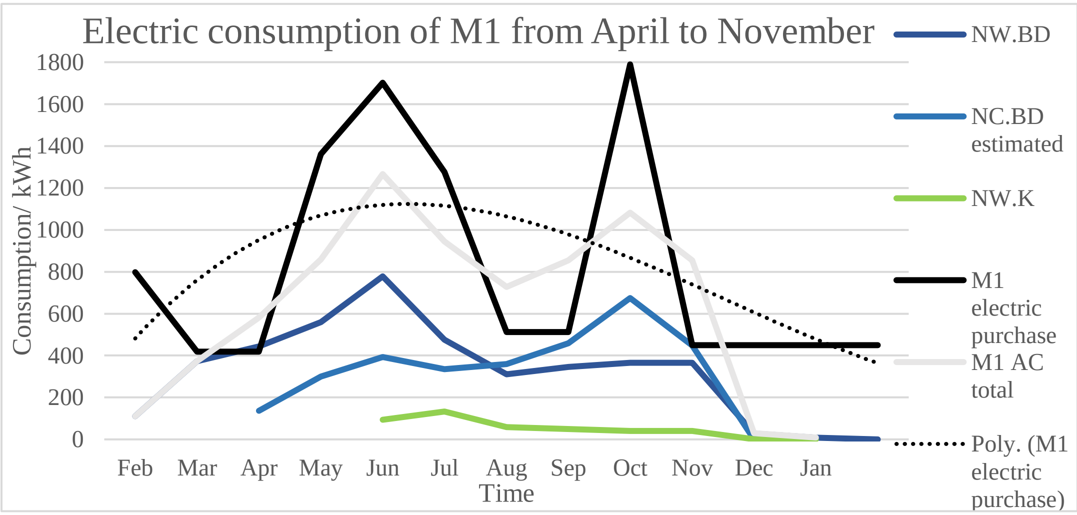


Figure 7.14 Electric consumption of the ACs in M1 from 02/2021-01/2022

In M1, the AC constituted the largest consumer of electricity purchased, consuming even more than the purchased amount in August, September and November. This is possible because the users had some electricity stored from the previous month. As noted by section 0, the AC usage period was extensive as the AC was only turned off from December to February and used extensively from April to November. The average monthly purchase was 814 kWh. The power was cut 12.4% of the time, so the users turned off the AC willingly over only 20% of the time when power was available.

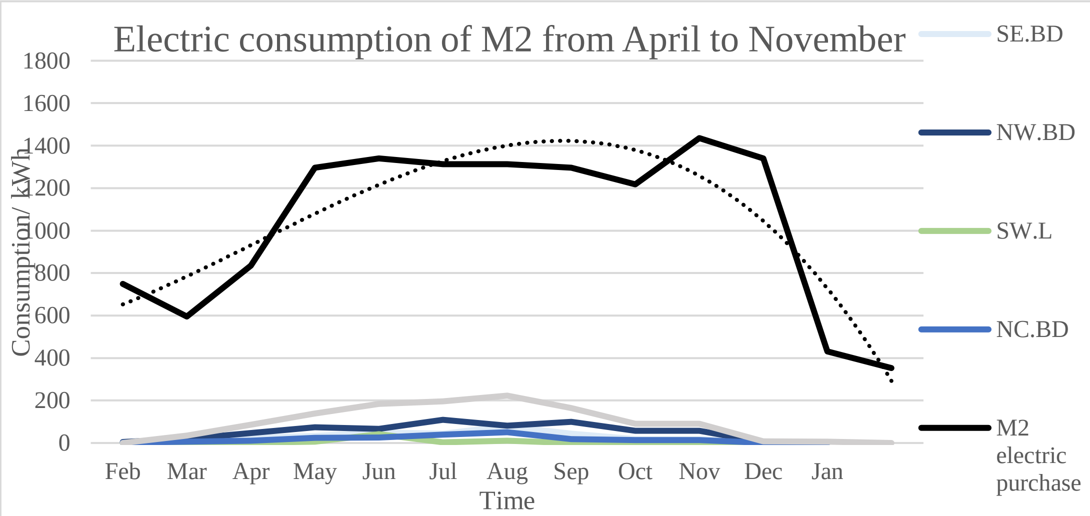


Figure 7.15 Electric consumption of the ACs in M2 from 02/2021-01/2022

M2 was distinct from the other case studies. Despite using the AC for fewer hours, reflected by less total AC electric consumption, their electric purchases were still similar to the houses T1 and M1. They were consistently around 1300 kWh, with an annual average of 1039 kWh. At its highest, the AC only consumed 17% of the total electric purchases in August. Part of this is explained by an evaporative cooler upstairs that was not logged. It could also be due to the use of other electrical appliances. The AC was turned off entirely from December to March and turned on extensively from May to October. The power was cut 18% of the time. Due to missing data in June and July, it was not possible to determine how long the AC in the bedroom NW.BD was turned on or when the power was cut. M1 and M2 reflect the higher expectations in Modern houses. In M1, this is through the more expensive refrigerant cooling. In M2, this is reflected in the high consumption rates from other sources despite needing to use the AC less than other buildings. This is similar to the rebound effect, where savings from improving the building fabric are lost as occupants adjust their lifestyle to the improved standards.

Figure 7.18 shows the monthly electric consumption of all the case study buildings over the study period. T1 consumed significantly more than T2 and T3, while M1 and M2 consumed similarly. The lowest consuming household T3 consumed year-round was above 600 kWh. This rate is significant given the fact that the house size is typical of a Sudanese house, and there are only three occupants who use the evaporative cooler minimally. Comparing this to the electric consumption rates of Sudanese households (The world bank, 2019), shown in Table 7.9, it is noticeable that this consumption level was considered among the top 3% in 2014. However, we know that air conditioner purchase rates have increased, as discussed in section 4.3. This table also includes other states than Khartoum, which consumes 70% of the country's electricity. Therefore, it likely has a higher percentage of its population in the higher consuming brackets.

Table 7.9 Percentage of Households and kWh Consumed by Tranche. Source: (The world bank, 2019)

	% of Households	% of kWh Consumed
Residential (0–200 kWh)	46	21
Residential (201–400 kWh)	46	39
Residential (401–600 kWh)	5	8
Residential (601–800 kWh)	1	3
Residential (801–1,500 kWh)	1	3
Residential (1,501+ kWh)	1	26

To estimate how much of Khartoum's population is likely to own ACs and consume in the higher brackets, the population increase needs to be estimated and linked to the AC import rates shown in Figure 7.16. The last population census happened in 2008, and the political instability after the popular uprising in 2018 makes it hard to make reasonable assumptions or find reliable statistics. The population from 2008 to 2018 increased by an estimated 2 million people. Given that the average household size is 6, the expected number of households in 2018 is around 1,198,115 houses. In 2008, 21% of households had air conditioners, around half of the middle class.

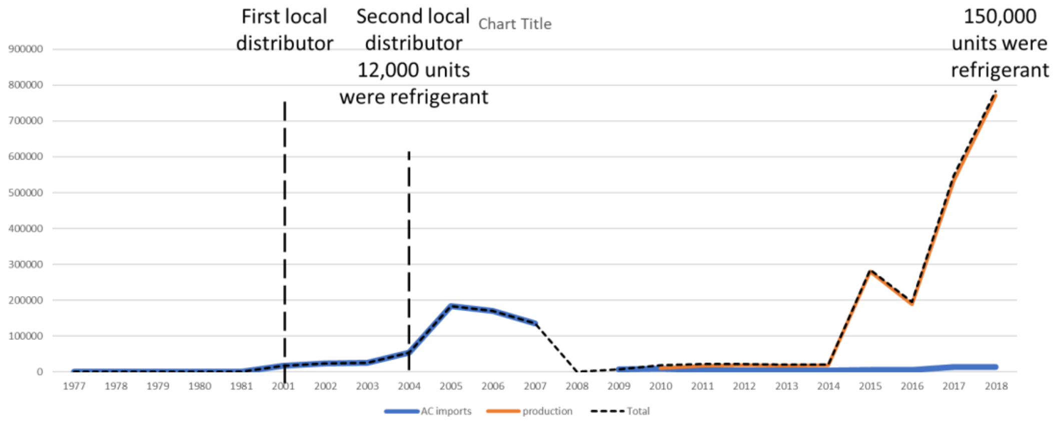


Figure 7.16 AC imports and production levels in Sudan (Source: various reports from Sudan bank)

Figure 7.16 shows that the total number of units imported to Sudan from 2003-2008, was around 630,000 units. Between 2013 and 2018, 1,900,000 units were imported, which is three times as much. if we estimate that 60% of these imports went to Khartoum with the average house purchasing 3, this means the estimated total number of households with ACs in Khartoum would be 534,728 households. This would mean that it is estimated that in 2018, 45% of households had an AC, which is the entire middle class and some lower classes. Our case study showed that T3, which is an average sized house, had only 3 occupants who used the AC minimally, consumed 600 kWh per month. Thus, a significant portion of Khartoum's population is consuming at a rate previously only consumed by 3% of the population in 2014, as shown in Table 7.9.

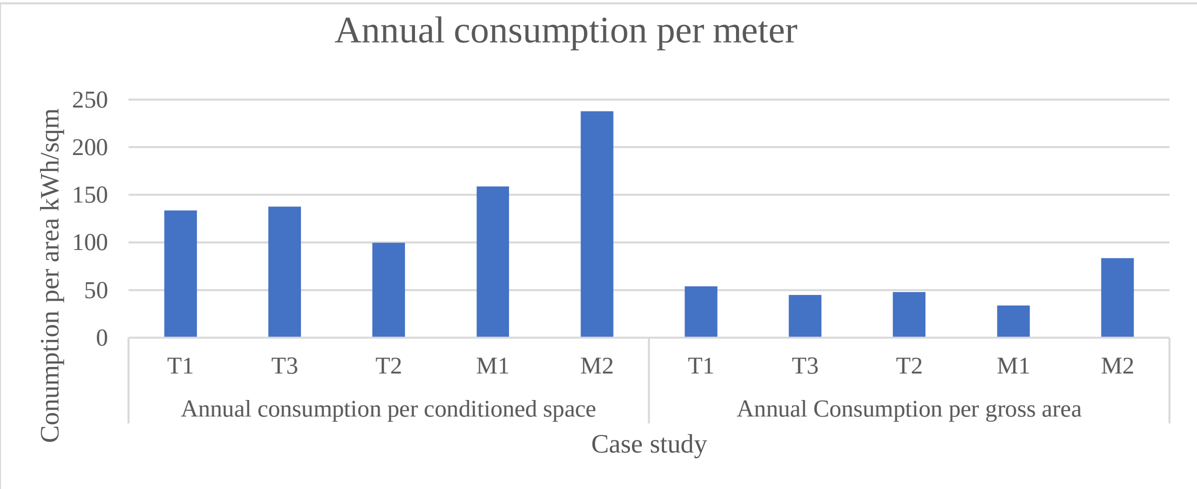


Figure 7.17 Annual electric consumption per square meter in the five case study buildings

When comparing the performance of buildings in different contexts and sizes, energy use intensity (EUI) is used (Schurk, 2015). EUI is the total energy a building uses in a year divided by its floor area. The internal gross floor area is used according to CIBSE TM46, which means internal walls are included in this calculation. In the TM46, a typical western house would consume 65 kWh/m^2(CIBSE, 2008); all our case study samples fall within this limit except for M2, which consumed 83 kWh/m^2.

However, this figure is for a '24-hour fully conditioned and serviced accommodation'. As mentioned, the case studies are mixed-mode houses, with large unused parts. This means the figures are not representative of their actual consumption levels. Dividing the consumption by the conditioned areas, which are the highest consumers and the most used spaces, the consumption per meter level increases to 100-237 kWh per meter, which is significantly higher.

The consumption levels shown in the case studies were higher than in many other developing countries but not as high as in Arab countries with similar climates but higher incomes. A Malaysian house consumes 648 kWh per month on average (Ali et al., 2021), while an urban Indian consumes a max of 1100 kWh with an average of 200 kWh (Singh et al., 2018). In more advanced economies, such as Saudi Arabia, houses consume 1000-4500 kWh per month (Giusti & Almoosawi, 2017),

7.5.Emergent behavioural themes

During the monitoring period, the occupants frequently changed their living arrangements and behaviours. They also responded differently to stresses such as power cuts, heatwaves, and increased energy costs. This section aims to capture those behaviours and also explore attitudes expressed by the occupants and how it can be linked to their usage patterns.

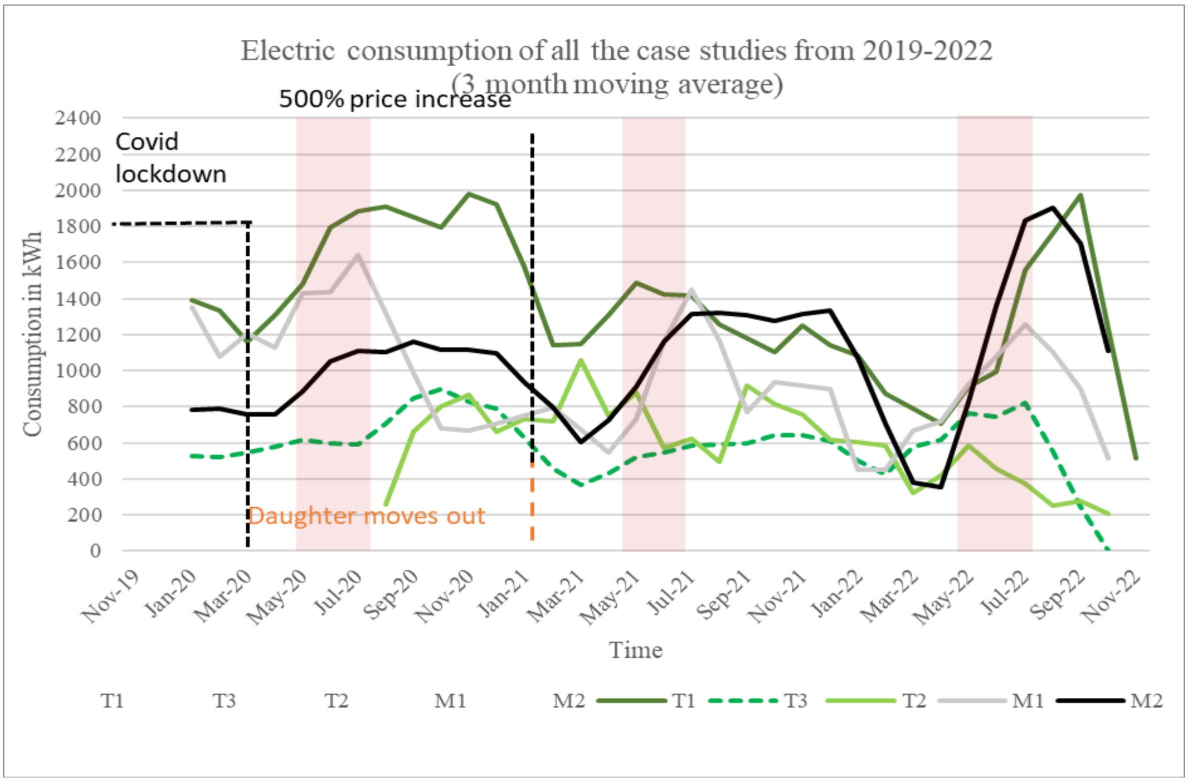


Figure 7.18 Electric consumption of T1, T2, T3, M1 and M2 from 2019-2022

In January 2021, electricity prices increased by 500% (Yassin, 2021). As shown in Figure 7.18, it caused an overall decrease in electric consumption for T1, T3 and M1. However, in T3, this decrease is attributed to the married daughter moving out in January 2021, as she was a significant energy consumer. T3 used to typically purchase 500-600 kWh at the beginning of each month. Then from July to December 2020, they supplemented this at the end of the month up to 1000 kWh. This could be because of the pandemic that made the daughter stay at home more. Their usage pattern was consistent throughout the year, and the daughter opened the AC as a habit. This contrasts with T1 and T2, which experience a winter drop. The occupants in T1 and M1 implemented behavioural changes to reduce their consumption. Behaviour-wise, the occupants of T1 and M1 reported trying to reduce their energy consumption levels by turning off lights and fans in unused spaces. The occupant in T1 said, *'it is hot these days and humid because of the fall, especially in al-Mogran, if I turn off the lights and the AC, the room would be filled with ants. So we try to turn off all the electricity on my side (the male side) except for the male bedroom and the living room; we try to limit the AC use to certain hours; sometimes we open it, sometimes not"*. These measures lead to a drop in consumption from 1800-2000 kWh to 1300-1400 kWh. M1 said that they had not seen a significant impact despite reducing their water pump and extra fridge use. People assume that curtailing their energy use and behavioural changes are more efficient than physical changes to the building to conserve energy (Lutzeinhiser, 1993). The occupants on the M1 are the only ones that made a building-level change as they added mosquito screens to the windows. This allows opening the window during the night when the power is cut off; therefore, it relates more to thermal comfort rather than reducing their electric consumption. The occupants in T2 felt that they were already consuming as low as possible and thus did not change anything and kept the same levels. In M2, the consumption levels seem to increase, but this is because the occupants divided the villa into three apartments and rented two in 2022, which meant an increase in occupancy levels for the same space.

Before the price increase, the households had already implemented different energy-conserving behaviours. In M1, the residents slept together in a shared room to cut the costs of using several split units. Another behaviour observed was that older residents in T2 restrict the usage rates of the AC in the house. To adapt, male residents in the Saloon T2-NE.BD use the AC mainly during afternoon siestas (33%) and open the windows at night to allow for cross ventilation. They said they also do this to prevent the room from getting 'stuffy' with the humidity from the evaporative cooler. They are the only occupants who open the window at night. This response to a restriction was also observed in a different case study (H1) performed by the author in 2019 (Elsherif et al., 2020). In T1, the AC in the living room T1-NC.L is turned on most of the day to cool nearby rooms that do not have an AC. At night a male occupant sleeps in the living room as his own AC does not work; however, it is scarcely used as a living room. The AC in the bedroom T1-SC.BD is used similarly to cool the adjacent bedroom ME.BD by leaving the door open between them. This extensive use is why in May 2022, the AC in the bedroom T1-SC.BD consumed 176 kWh, and the one in the living room T1-NC.L consumed 149 kWh. Using one AC to condition two spaces has been observed in another case study (H5) by the author (Elsherif et al., 2020). This could also explain why the internal thermal conditions in the bedroom T1-ME.BD are comfortable despite not having an AC. These observations overall highlight that understanding the occupants' behaviours is important to understand thermal readings, as they reflect both the fabric's and the occupant's impact.

During the monitoring period, all the case studies (except T3) either added an extra air conditioner, fixed a broken one, or upgraded an existing one from an evaporative to a split unit. The summer heat wave in 2021 coincided with Ramadan, which pushed the occupants to improve their thermal comfort. Fasting is harder to do during hot periods as they are not allowed to drink water, which makes dehydration from sweating a risk. The occupants in T2 installed an AC in bedroom T2-NC.BD in preparation. During that heatwave, it had been heavily used both day and night by a younger occupant on vacation from college. The daily power cuts exacerbated the pressure from the heatwave, with news reports of people resorting to buying ice to cope (Xinhua, 2021). During a power cut, the residents are forced to use natural methods such as spending the evenings and nights outdoors, taking a shower, seeking cooler areas of the house, and opening the windows. However, as these methods are sometimes ineffective due to mosquitos, water shortages and poor wind speed, they started adopting hybrid methods. Residents in T1 and M2 have installed batteries that power one fan, one light bulb and a few sockets to avoid going outdoors. As the battery has a small capacity, it was observed that they prioritise using it when it gets hot or they need to sleep. The fan is the priority; they even keep the lights off to extend its use. Residents in M2 used to set their split unit to 27ºC but now set it at 18ºC to cool the building as much as possible in preparation for the power cut. They then rely on a battery to power a fan and sleep on the cool tile floor. This behaviour increases the electric consumption of the split unit in the bedroom NW.BD. It consumed 778 kWh in June 2021, which is higher than the consumption of the entire building in T2 for the same month. As heatwaves are expected to become more frequent due to climate change, understanding how occupants respond to them now will help develop strategies to avoid these energy-intensive ad hoc solutions.

Naturally ventilated spaces were usually too hot to use in the summer, which created a difference in summer and winter use. This variation was observed in M1; the female Millennial does not use her actual room 1.SE.BD unless it is winter. It stores her belongings for the rest of the year. She mentioned that it is so hot that her toiletries melt when left there. This is further explored in section 8.4. In T1, the unconditioned space ME.BD, at the beginning of the study, was just a store. However, during a subsequent visit in February 2022, it was observed that the Gen Z female occupant converted into her bedroom, most likely to seek more privacy. In the beginning, the girls mainly spent their evenings socialising instead of using the other bedroom NE.BD but rarely used to sleep in it as it does not have an AC. This pattern changed in the winter when the temperatures were cool enough to use it day and night.

The impact of distinct individual behavioural patterns on thermal conditions was captured in M2. As mentioned previously, the occupants in M2 moved from the upper floor to the lower one after they converted their villa into a hybrid. The boys and the parents switched room locations which provided an incredible chance to compare the influence of usage patterns on the rooms' thermal profiles.

Figure 7.19 shows the average temperature deviation every hour of the day for the M2 on the ground and first floor in May 2021 and 2020, respectively. The shaded red zones show how many degrees hotter the space was from 30.9ºC, on average. As mentioned in section 2.2.4, 30.9ºC is Khartoum's maximum summer comfort temperature. The dark red line is the external temperature, which helps visually compare the figures.

The outdoor temperatures recorded by the data logger show an average peak at 2:30 pm, and it was the coolest at 7:30 am. The dotted lines mark noon. Yellow lines denote unconditioned rooms, while blue lines denote conditioned rooms.

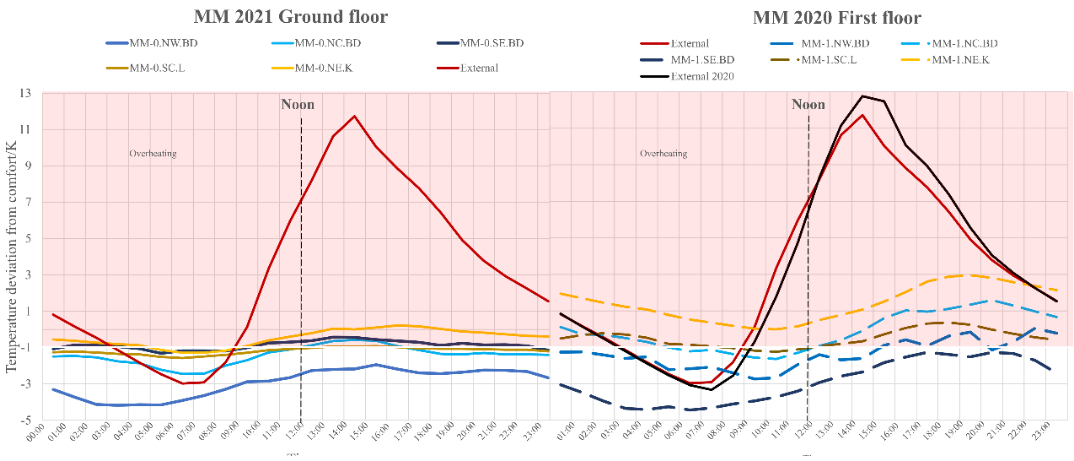


Figure 7.19 The temperature deviation from comfort in MM during the hot season in 2020 (right) and 2021 (left)

In both graphs shown in Figure 7.19, the room occupied by the boys was the coolest. On the upper floors, the teenage boys used room M2-SE.BD with the AC on for 11 hours compared to just 2-3 hours used by the middle-aged parents in M2-NW.BD.

This made the bedroom M2-SE.BD, the coolest room on the floor in 2020. When the family moved downstairs, they switched rooms, which made the thermal profile seen in M2-NW.BD and M2-SE.BD also switch. The coolest room was now M2-NW.BD in 2021. The female daughter that lived in the bedroom M2-NC.BD used the AC at a rate that was only slightly higher than her parents. These findings confirm observations in the other case studies that older users tended to use the AC less, and females also used the AC less than males. Studies have shown that women take conservation more seriously than men (Lutzeinhiser, 1993; Altman, 2014), which could be a contributor. In terms of thermal comfort, there is a disagreement among them. While some find no difference between male and female thermal comfort (Merghani & Hall, 2001), others find that women preferred a higher comfort temperature of up to 0.8K (Maykot et al., 2018). women are also more likely to express discomfort at cooler temperatures but will adjust their clothing accordingly (Zhai et al., 2014).

7.6.Conclusion

Previous chapters showed that before air-conditioning was introduced, the Sudanese home relied on thermal migration. The occupants constantly moved from different parts of the yard to the veranda and only used the living room during siestas. The internal space was usually small compared to the overall yard space. This migration was aided by the portable nature of appliances such as portable coal stoves, washing clothes and dishes in a bucket, and movable beds and chairs. Gas stoves, washing machines, fixed sinks, and heavy sofas replaced these fittings. Another critical aid was activities that happened in outdoors, such as taking care of animals and plants and socialising, both of which decreased with modern life due to limited time. Finally, as cities grew, the reduced security and privacy limited yard and window use even further. Thus, adopting the AC is another symptom of a broader modernity transformation.

This chapter explored how this modernisation impacted the everyday usage patterns of occupants. Firstly, there was a complete abandonment of outdoor space use, except for special occasions and power cuts. Even then, when batteries became available, they preferred to stay in the sheltered indoors. The only occupant who regularly used the yard and balcony was a male retiree. When we look at internal use of spaces, bedroom use is extensive in younger, more active generations such as Gen Z, Millennials and some Gen X. While older generations like retired Gen X and Boomers used the living room more extensively and usually had a siesta in the bedroom as in M1, M2, T1 and T2.

To aid this extensive internal presence, ACs were used to cope. This results in a long cooling season that extends the entire eight months in most cases, with extensive hours reaching a daily average of 17 hours per day. This fact is concerning given that the power cuts 16-25% of the time, meaning that AC use would likely have been almost constant without those power cuts.

This extensive AC use was reflected in the high kWh consumption of the houses. They all consumed higher than other developing countries that have better economies. The increase in the cost of electricity did not decrease the house's consumption significantly. Instead, the increasing power cuts and heat waves have pushed the occupants to adopt more consumptive behaviours rather than revert to adaptive practices or improve the building. The occupants' lack of grasp of the extent of their consumption makes them less likely to implement drastic changes. Consumption habits also differed between occupants, with younger generations being more likely to consume more and spend more time in their own bedrooms. Younger generations in Sudan grew up during the economic boom, making them more likely to be higher consumers and exhibit individualistic behaviours. This is because, as mentioned in the introduction, a better quality of life increases the chances that comfort becomes a priority. In one case, the occupant slept in the living room from his dependence on the AC.

These findings highlight the extent of the consumption issues in the Sudanese house and the need for change. This intervention could be in the form of behavioural changes or changes to the building. To make these changes, it is essential to understand how the building is coping thermally with the current usage patterns. This understanding will help quantify how much overheating occurs and when so that design solutions can affordably target the extremities. This chapter identified the times users use the spaces the most, which is when the building must be comfortable to avoid excessive AC use. This tailored approach is necessary as finances are limited, and occupants cannot afford to upgrade the entire house.

Chapter 8 The thermal toll of modernisation

8.1. Overview

After studying the occupant's use of the building in the previous chapter, this chapter focuses on understanding the building itself and its thermal performance, in light of the role of building fabric and AC technology. It utilises solar radiation analysis, thermal imaging and building monitoring to achieve this goal. The impact of building form, fabric and AC will be analysed separately first before looking at their collective impact on internal thermal conditions. Finally, any additional problem areas uncovered through the fieldwork will be detailed.

Switching from vernacular to modern building materials comes with many consequences, including operational energy implications. The operational energy impact comes from the different thermal performances of these materials. The changes to our case study buildings go beyond the 'skin' layer, as they also encompass the structure, the services, the space plan and the 'stuff', as discussed in section 5.1. The negative thermal impact of these changes was mentioned by the occupants of T2 and T3 in chapter 5, along with their coping mechanisms to mitigate the increasing temperatures. This chapter aims to go beyond just quantifying this thermal discomfort, but to understand the changes that occur in the thermal environment through time, both daily and seasonally. This means finding out both when overheating occurs and to what extent.

From a heat balance perspective a person interacts with their thermal environment predominantly through air convection, radiation and evaporation. Thus these are the parameters this chapter will focus on. The internal thermal environment of the building is impacted by both the building's form and fabric. The form impacts how much solar radiation reaches the building, while the fabric controls the rate at which that radiation and air convection enters the building and potential for ventilation. Assessing the building's performance is more straightforward when the building is free running, but our buildings are mixed-mode. The air conditioner introduces a host of new factors to assess, such as the number of hours the AC was used, the condition of the air released by the AC, and how well the building maintains that cool air. Therefore, as mentioned, this chapter will assess the building form, fabric and HVAC separately before assessing the building's performance as a whole.

8.2. The impact of building form on solar radiation exposure

Triangulating the quantity of solar radiation impacting the case study buildings was done through three methods. First, a literature review was conducted to understand the underlying factors that link a building's form with the amount of solar radiation it receives. This data was then be applied to our case studies to theorise their possible performance. Secondly, modelling using the Revit insight plugin, gave an indication of expected cumulative solar radiation on the different building surfaces. Both methods focus entirely on the impact of form but not materials. Finally, thermal imaging showed the combined impact of form and fabric on the amount of radiation entering the building in the next section 8.3.1.

Surface to volume (s/v) ratio is the primary tool to assess building form. It is the amount of surface area for different forms with the same volume. A detached house has a ratio of 0.72 or more, a terraced house has 0.57-0.71, A row house has 0.46-0.56, and the least is a tower which has 0.45 (Torabi Moghadam et al., 2016). A low s/v ratio is preferred in hot climates to reduce the external space exposed to outdoor conditions, particularly the sun (Behsh, 2002). It reduces cooling loads by reducing heat transfer, which preserves cooled air in the building. These properties make buildings with low s/v ratios take more time to be impacted by outdoor conditions. This is acknowledged by standards like Passivhaus, which encourage a smaller ‘form factor’, as it means a more compact a building. Buildings, however, also need some external space to maintain daylight and ventilation (Ratti et al., 2003), especially night ventilation in hot arid climates. Therefore, a balance needs to be established. In areas with a large diurnal swing, traditional houses have different (s/v) ratios and thermal mass combinations to produce a variety of thermal conditions in rooms. Summer rooms are smaller with larger thermal mass, while winter rooms are larger with lighter structures (Behsh, 2002).

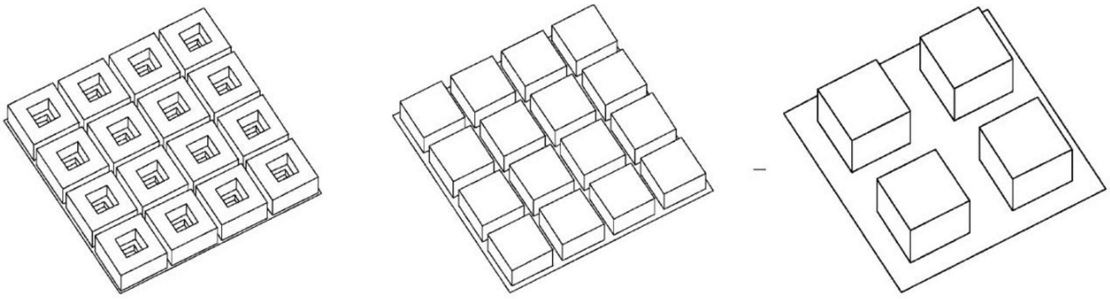


Figure 8.1 Axonometric representation on a 67.5m x 67.5m site of the traditional Arabic courtyard (Left: three-floor courtyard) and of two pavilion structures (middle: micro-pavilion, three floors: right: pavilion, six floors). Source: (Ratti et al., 2003)

Ratti et al. compared the thermal performance of three typologies and found that the courtyard house typology had the highest s/v ratio, followed by the micro pavilion and then the pavilion; these typologies are shown in Figure 8.1. It should be noted that the courtyard typology displayed by Ratti shows streets between individual buildings, which is not the case in an Arab courtyard. Most buildings are attached from three sides, which reduces the amount of externally exposed walls (Behsh, 2002). Also, the courtyards offset this high surface area using the expansive and heavy thermal mass walls to store the heat for night-time use.

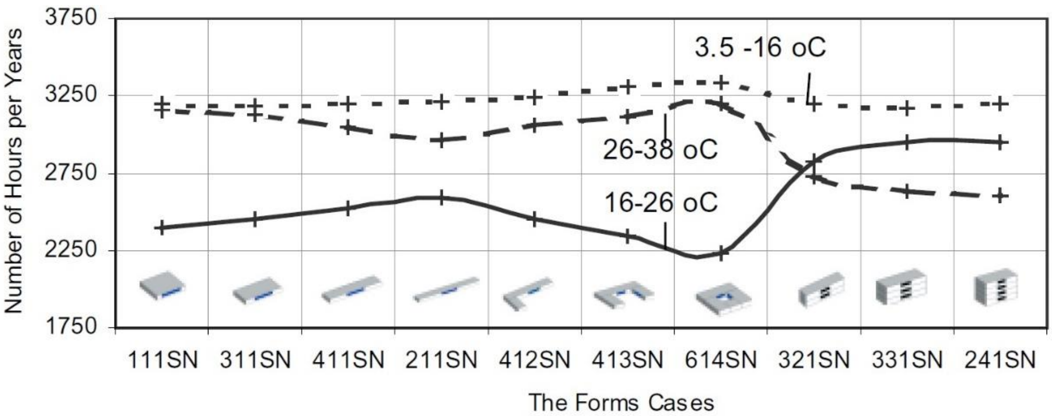


Figure 8.2 A comparison between different building forms and their temperature ranges in hours per year. Source: (Behsh, 2002)

Behsh analysed the s/v ratio of different building shapes with the same volume and their impact on the hours per year within three temperature ranges, as shown in Figure 8.2. He compared the impact of square shapes compared to rectangular ones, simple shapes compared to more complex ones, and the impact of reducing the roof area by making the building more compact. He also included different orientations of the same shape. The shapes 111SN-411SN in Figure 8.2 show that the rectangular shape had a higher number of hours within 16-26, indicating better performance.

Though this seems to contradict the fact that square shapes have a smaller s/v ratio than rectangles, it is because the lack of natural sunlight in the deep areas of the square makes the building more dependent on artificial light (Catalina et al., 2011). The rectangle shape also performed better than the courtyard, the U-shape, and the L-shape. This is probably because these shapes are less compact. It should be noted that although complex shapes typically have higher s/v ratios, the s/v value becomes a less reliable measure of climatic performance (Behsh, 2002). Thus, modelling is needed to more accurately confirm any assumptions in these cases. Finally, Behsh found that east-west orientations receive less radiation due to reduced exposed western walls. This observation is another reason rectangular shapes work better than square shapes, provided they are oriented in which the small side is in the west.

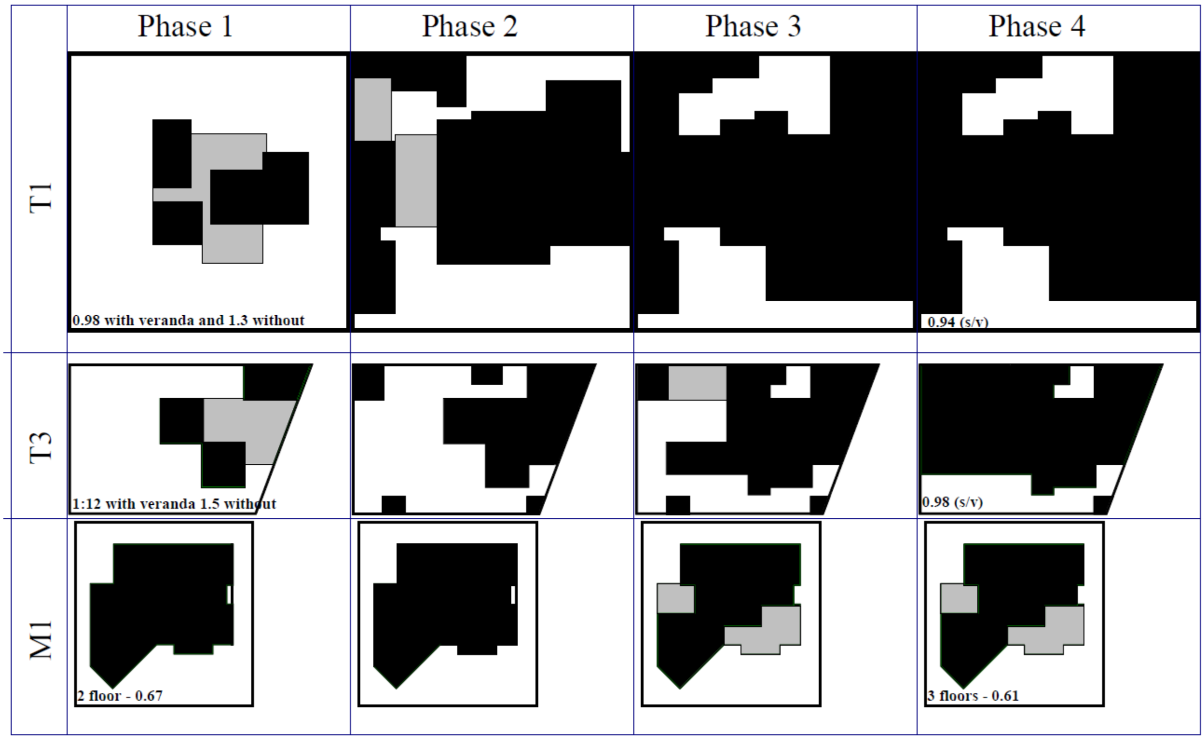


Figure 8.3 The s/v ratio in T1, T3 and M1 as they changed

Before analysing the performance of the current forms of all five buildings, this section will look at the impact of change in three cases that changed significantly. Figure 8.3 shows the calculated S/V ratios for T1, T3 and M1 as they changed from phase 1 to phase 4. They were calculated manually by dividing the building's surface area by its volume. It shows that the building expansion decreased the s/v ratio slightly in T1 from 0.98 to 0.94 and in T3 from 1.12 to 0.98. This would likely have a negligible impact, especially given the complexity of the shapes. Therefore any thermal impact from the expansion is likely due to the loss of shade from verandas rather than the change in overall form. The building went from shallow with intermediate spaces that blur the outdoor transition to a deep building divorced from its surroundings. On the urban scale, this represents a shift from a pavilion layout to a micro pavilion (Ratti et al., 2003); it was never a typical courtyard house, as discussed in Section 2.1.

In the case of modern case study house M1, adding a floor lowered the s/v from 0.67 to 0.61 (Figure 8.3), which is also a relatively small change. The larger difference is seen when comparing the s/v ratio of the modern multi-story building to the traditional ground floor ones. Beshsh theorised that multi-story buildings perform better due to the reduced exposed roof area (for the same volume) compared to the wall space. Roofs receive the most radiation (Behsh, 2002).

Table 8.1 The roof-to-wall ratio in the case study buildings

	Roof area	**External wall area**				**Roof-to-wall ratio**
		Total	Exposed	Shaded by cover	Part of another building	
T1	388	414	413	42	48	**0.93**
T2	164	170	110	0	60	**0.96**
T3	175	177	81	0	96	**0.98**
M1	178	546	543	3	0	**0.32**
M2	166	339	276	63	0	**0.48**

As Behsh's study found, multi-story buildings had a lower roof-to-wall ratio, with the modern buildings having a ratio of 0.32-0.48 and the traditional ones 0.93-0.98, as shown in Table 8.1. Table 8.1 also shows that the traditional buildings had a portion of the external wall shaded by another building. This is either because they were built before planning rules or because of the subdivision into separate units. All the buildings had a similar roof area except T1, which is twice the size of the other houses, but if we exclude the store areas, the used space is $253m^2$.

Solar radiation modelling

Revit's plugin Insight was used to visualise the cumulative solar radiation the building was exposed to during the summer. The images do not reflect the material's properties, only how much solar energy falls on the surface based on its orientation. The images show that the expansive roofs on the traditional buildings received a significant amount of radiation, evident by the bright yellow colour.

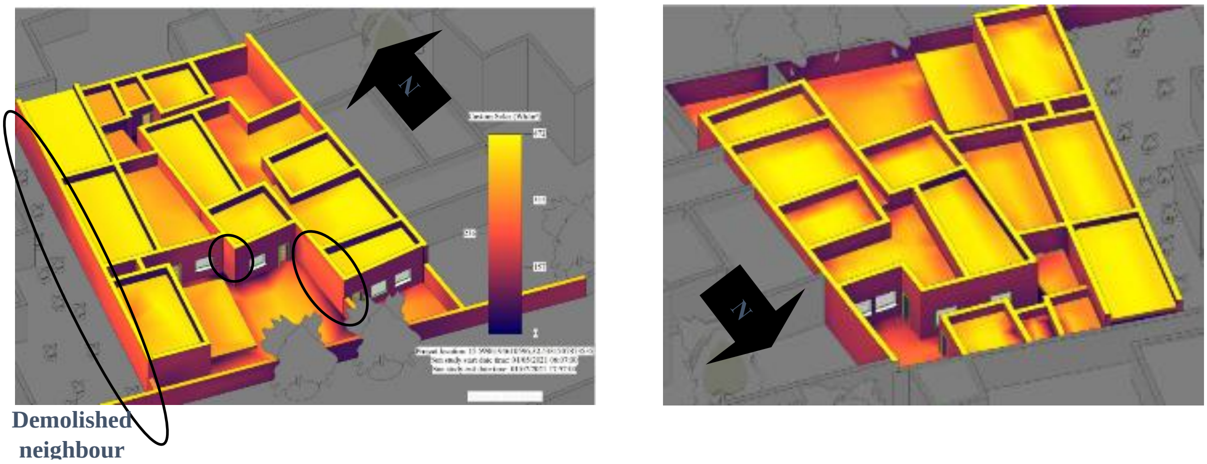


Figure 8.4 Cumulative solar radiation analysis of T1. Left: Southern view. Right: Northern view

Figure 8.4 shows that in T1, due the buildings form, it has an extensive roof but limited exterior walls. The roof received the most sunlight followed by the southern walls and then the northern walls. These findings match the thermal photos taken by the thermal camera. Interestingly, due to the close proximity of the eastern neighbour, the building doesn't have any exposed eastern walls. The western wall used to be shaded by the large tree but now that area is just open shrubs.

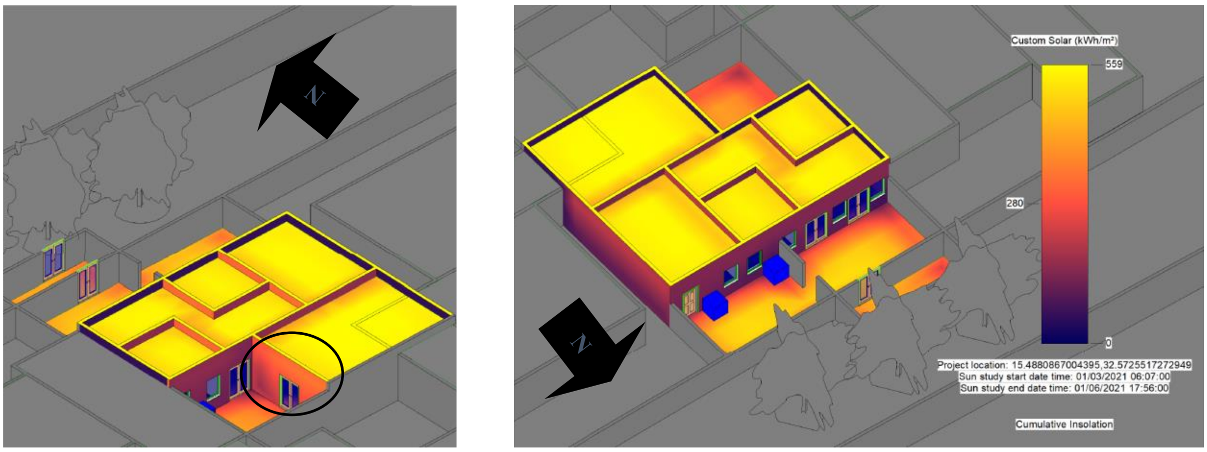


Figure 8.5 Cumulative solar radiation analysis of T2. Left: Southern view. Right: Northern view

In T2, the western and eastern sides were shaded by the neighbours, and only the northern and southern walls were exposed (Figure 8.5). The western wall of the veranda SW.L (circled) received almost as much radiation as the courtyard. Similar to T1, the neighbour demolished their building, further exposing the veranda.

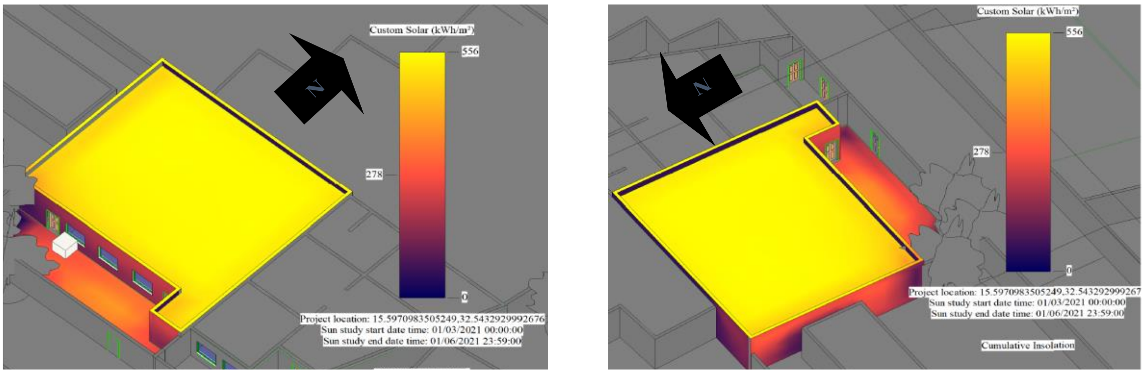


Figure 8.6 Cumulative solar radiation analysis of T3. Left: southern view. Right: Northern view

Figure 8.6 shows that building T3 only has an exposed southern wall and part of the western wall. The small front courtyard seems somewhat shaded by the building and the wall.

In modern buildings, the greater height of the building and smaller footprint means that the amount of exposed roof is much smaller than the traditional buildings. In M1 (Figure 8.7), despite adhering to the setback law, the North, East and West walls are shaded by neighbouring properties because they are multi-storey. Interestingly, the West walls are more exposed on the upper floors than on the lower floors. This is probably due to the fact the shade from the neighbour is less there. The building and neighbours also shade the North balconies shown in Figure 8.7 more compared to the southern balcony.

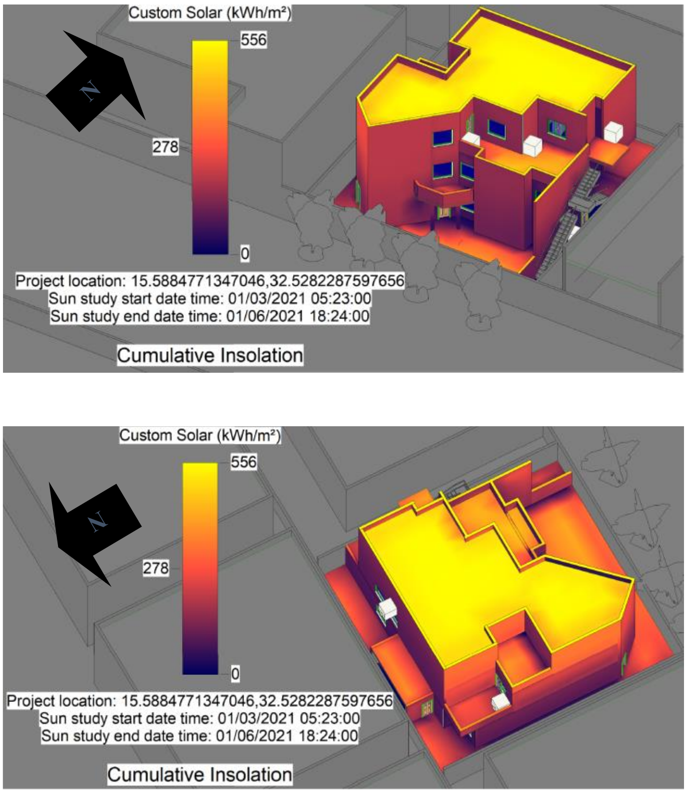
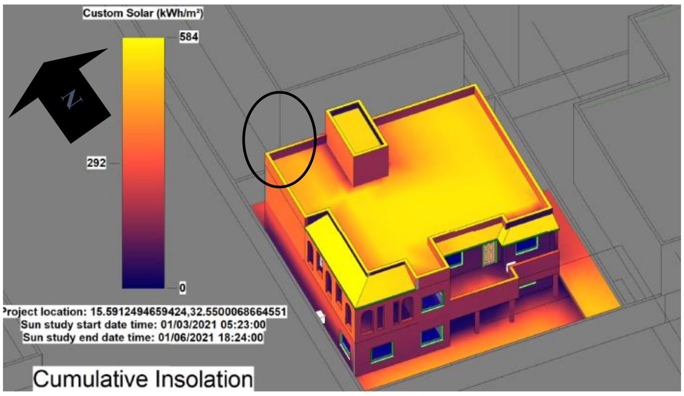


Figure 8.7 Cumulative solar radiation analysis of M1. Top is Southern, bottom is Northern

The South Façade of M2 is well-shaded by the balconies (Figure 8.8). Only a small portion of the wall is unshaded at the Southwest corner. The West façade is shaded on the ground floor by the boundary wall but is more exposed on the upper floors, except where the balcony provides shade. Neighbours shade the north and eastern walls. These walls also show a gradient where the upper parts are more exposed than the lower parts, but it is not as severe as the difference in the western wall in M1.



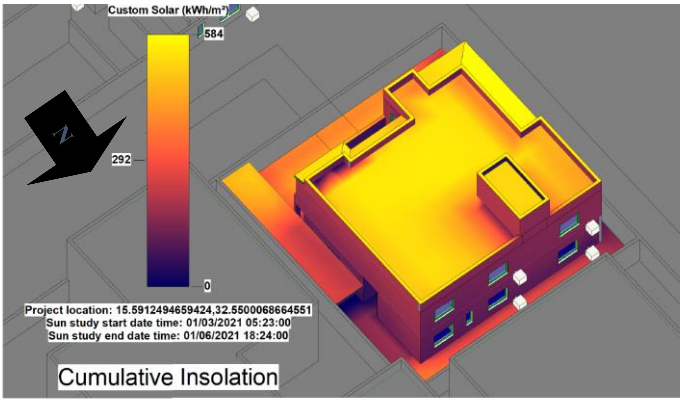


Figure 8.8 Cumulative solar radiation analysis of M1. Top: Southern, Bottom: Northern

8.3.The performance of building fabric and its impact on thermal comfort

Hot climates are divided into hot-dry and hot-humid climates because they require different passive strategies. While both emphasise shade, hot-humid climates require increased ventilation, while hot-dry climates benefit from lower ventilation rates during the day and higher ones at night. This is because hot-dry climates have a high diurnal swing. Lightweight materials tend to follow this daily pattern without much delay or dampening. This is why many buildings in the region utilise materials with high thermal mass, meaning they can store the heat during the day to release it during relatively cooler nights. However, in Khartoum, summer nights do not cool to 4ºC like the Sahara desert in North Sudan, but to a warm range of 25-30ºC, hindering the buildings ability to dispatch the heat collected during the day. This makes the internal peak higher as the overall amount of heat the building receives is more, which leads to a smaller day comfort window. This is reflected in Figure 8.9 which shows that temperatures in a high thermal mass house in Khartoum were below 31ºC for just 3 hours between 9am-12pm.

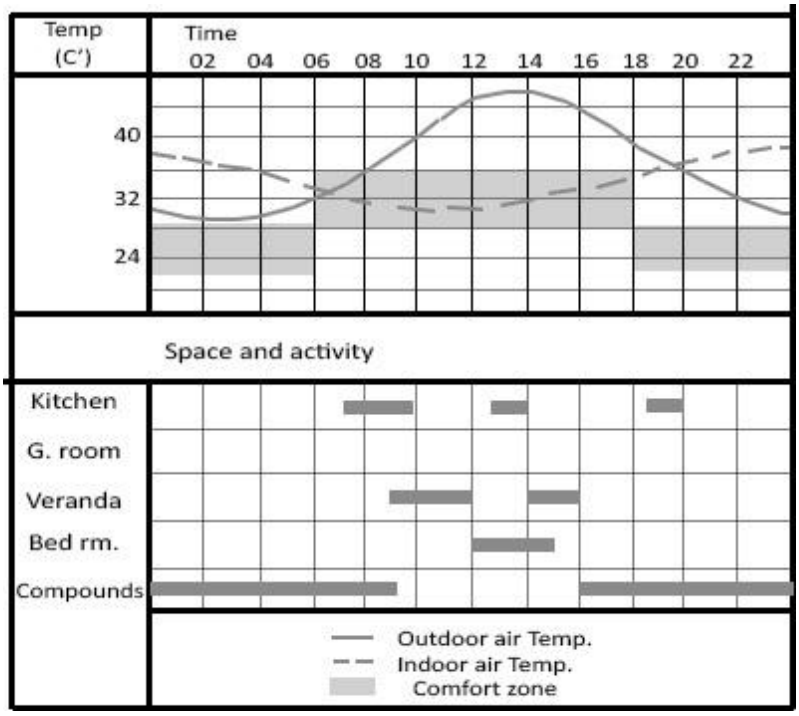


Figure 8.9 Space use and daily temperatures in a traditional setting. Source: (Ahmed,1978)

The second implication is that the indoor temperatures become exceptionally hot at night, reaching 39°C at night, so residents traditionally adapted by sleeping outdoors. This behaviour is also seen throughout North Africa and the Middle East, with the 'outdoors' being roofs, verandas or courtyards. (Saini, 1980).

This migration was part of a wider daily migration throughout the house, seeking refuge in the coolest part of the house. The house supported this migration with the thermal diversity it provided. Figure 8.9 shows how people synchronised their daily usage patterns with the thermal conditions in the building. Indoor rooms were only utilised during noon when they were the coolest, while different parts of the yard were cool during evenings and nights. Verandas covered the transition times.

Thermal mass alone is insufficient in Central Sudan because of the warm nights, however when combined with adequate shading, it performs better. Chapter 2 mentioned that houses in Sudan were typically scattered rooms, which meant high solar exposure to the walls. A study of traditional houses in Algeria, found that they kept the temperatures within 32-33°C throughout both the day and night (Bassoud et al., 2021), compared to the 31-39°C range in Khartoum. These houses are located in a similar climate with similar construction methods, the key difference is the medina style layout which provided extensive shading. However, even this smaller range is unacceptable by modern standards and active cooling would be needed, highlighting the limitations of passive cooling in extreme climates.

People replaced high thermal mass materials such as mud, wood and straw with thin brick walls and corrugated iron (Ibrahim & Omer, 2014), which disrupted the delicate balance between occupants' schedules and the building. These materials were chosen due to increased durability (Adounkpe et al., 2013) and social status. Many rooms were also later upgraded with false ceilings and ceramic tiles instead of the bare floor.

This section aims to assess how these new building fabrics perform both daily and throughout the year. As mentioned previously, our key parameters are radiation, convection and evaporation. Solar radiation will be assessed through thermal imaging. To explore the impact of air convection, indoor air temperatures will be used as a performance indicator. Evaporation cools the body through sweat, a process that high humidity levels and low wind speeds can hinder. Humidity levels are impacted by evaporative coolers and the efficiency of the building's ventilation more than the building fabric itself. Therefore, it will be further explored in section 8.4. when we investigate the impact of the AC.

Solar radiation and its impact on building material's diurnal swing

The modelling in the previous section showed the predicted total radiation incidence throughout the summer. However, it does not reflect how much of that radiation transfers through the building fabric throughout a single day. Thermal images were taken at 12 pm and 5 pm to evaluate this effect in May 2020, with the exception of T2 which only has 12pm images. This is due to the inability to revisit the site later in the same day, as T2 was added later in the project. Thermal cameras measure the infrared energy of objects, which typically indicates how hot an object is. Low emissivity surfaces are challenging to measure using thermal cameras as they reflect the temperature of surrounding objects in addition to their own temperatures. Therefore, the emissivity settings in the camera were adjusted according to the values in Table 8.2. The reflected air temperature was assumed to be 30ºC rather than the default camera setting of 20ºC, as air temperatures are hotter in Sudan.

Table 8.2 Emissivity of various building materials in our case study buildings

Material	Emissivity	Material	Emissivity
Tile	0.97	**Old galvanised steel**	0.88
Glass	0.89	**Plaster**	0.96
Paint	0.96	**Porcelain**	0.92
Gypsum	0.85	**Concrete tiles**	0.63

The images show the combined impact of the building material and the orientation of the surfaces because they both contribute to the amount of energy received and emitted by building objects. The bright yellow parts indicate the most heat gain, which was always the roof. Roofs in Sub-Saharan Africa contribute to 70% of a room's heat gain due to the high sun altitude (Adounkpe et al., 2013). Hence, this section will focus on the different roof types in our case study buildings. To further aid the comparison, the tables include the construction details and thermal specifications of the three roof types. Akram estimated the U values and thermal decrements of typical Sudanese roofs using Ecotect analysis (Elkhalifa & Balila, 2014).

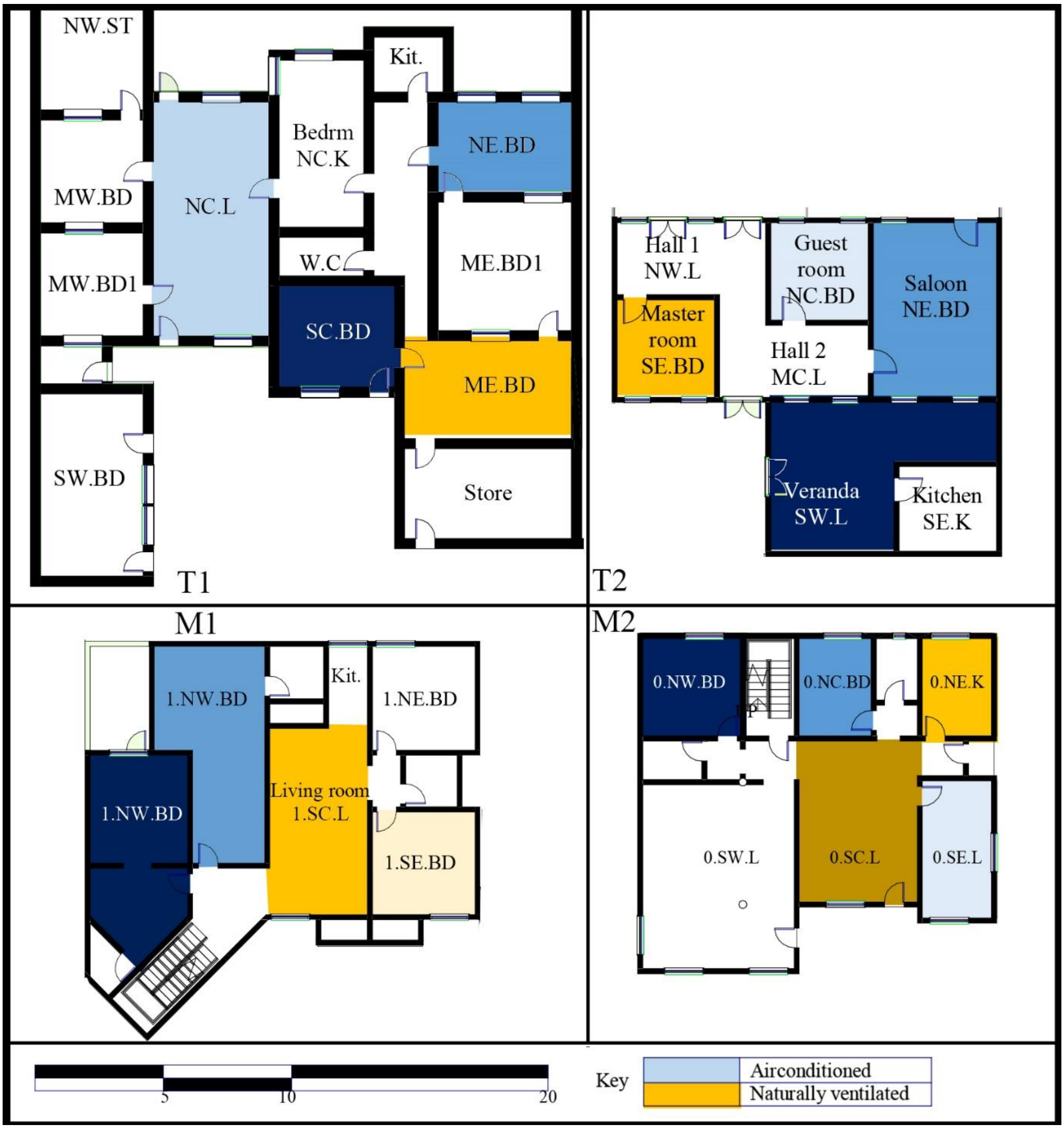
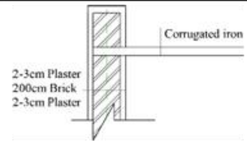
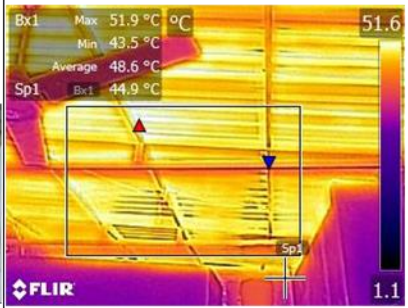
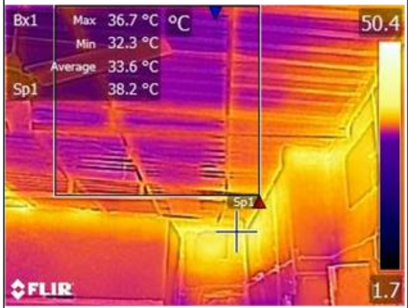
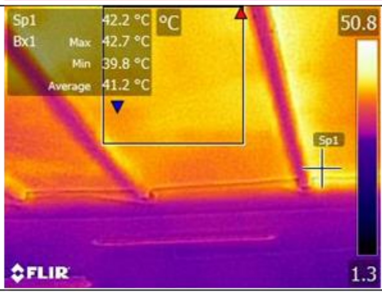


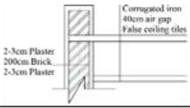
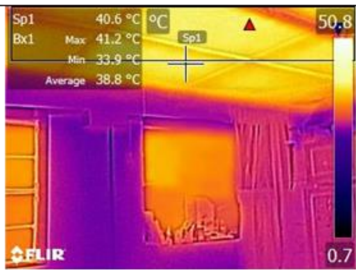
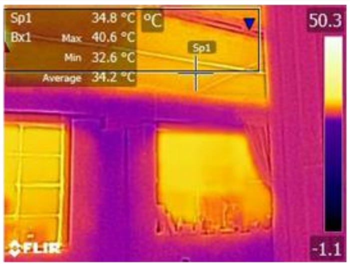
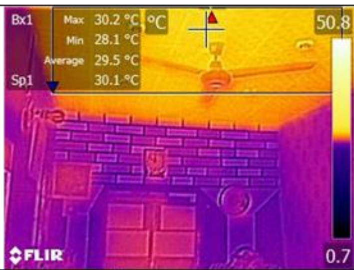
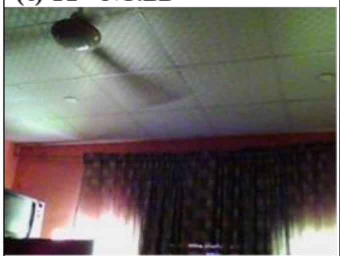
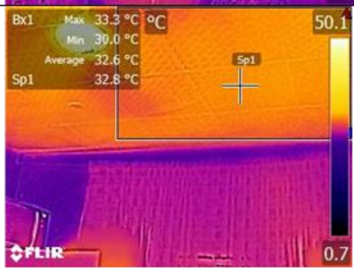
Figure 8.10 Master key showing the sampled spaces in T1, T2, M1 and M2

Table 8.3 Corrugated iron roof thermal images

<table>
<tr><th>Iron roof</th><th>Noon</th><th>Sunset</th></tr>
<tr><td>
</td><td>U value: 5.62 w/m²K</td><td>Thermal decrement: 0.98</td></tr>
<tr><td>(a) T1 - NW.ST
</td><td>
</td><td>
</td></tr>
<tr><td>(b) T2 – SW.L
</td><td>
</td><td>Missing</td></tr>
<tr><td>(c) T3-MW.L</td><td>
</td><td>
</td></tr>
<tr><td>(d) Wooden roof in T1 – MW.BD</td><td>
</td><td>
</td></tr>
</table>

The corrugated iron roofs (Table 8.3) were the hottest roof type. Temperatures reached 51.9ºC at noon in T1, which was hotter than the external air temperature of 38.5ºC recorded by the data logger. Though the internal air temperature was only 33.9ºC, the radiation from the hot roof would cause discomfort. By sunset, it had cooled significantly to around 33ºC. The images in section (d) are for wooden roofs, the hottest roof type in the evening, cooling from 41.2ºC to 37.8ºC.

Table 8.4 False ceiling's thermal images

False ceilings	Noon U value: 2.33 w/m²K	Sunset Thermal decrement: unknown
		
(a) T1- NE.BD 		
(b) T2 – NE.BD 		Missing
(c) T2 – NC.BD 		Missing
(d) T2 – MC.L 		Missing

The false ceilings shown in Table 8.4 created a double roof that did not heat as significantly as the iron roof. This is confirmed by other studies (Saini, 1980). At noon, their average varied from 29.5-40.6°C, then cooled to 30.2°C-34.2°C, usually around 4K cooling. This means that they had not cooled as much by sunset as the corrugated iron roof. This results from the corrugated iron being directly exposed to the sky, allowing it to radiate its heat faster. These findings align with the thermal corrugated iron roof studies conducted in Burkina Faso, a Sub-Saharan country with a similar climate (Adounkpe et al., 2013).

Table 8.5 Concrete roof thermal imaging

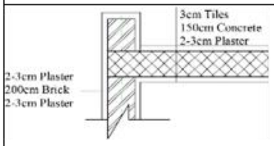
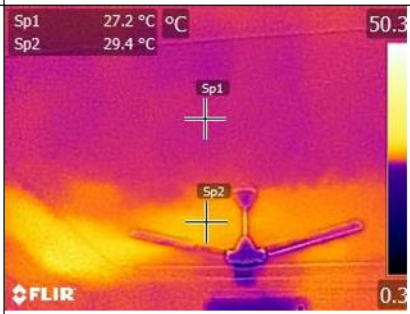
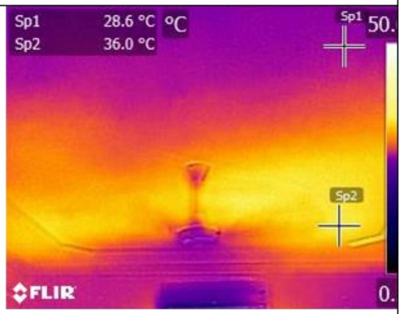
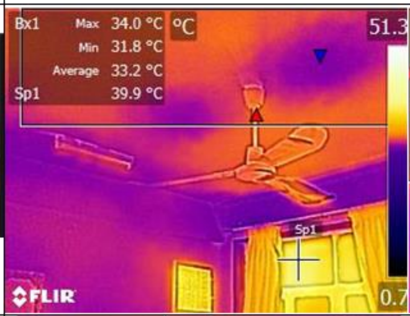
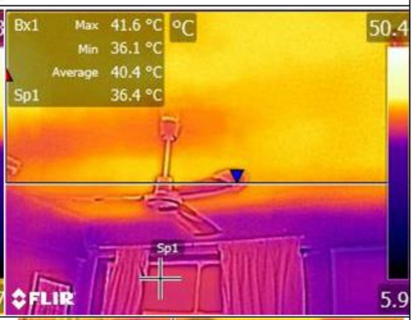
<table>
<tr><td>Concrete roofs</td><td>Noon</td><td>Sunset</td></tr>
<tr><td>
</td><td>U value: 1.09 w/m²K</td><td>Thermal decrement: 0.74</td></tr>
<tr><td>(a) M1 – NW.BD
</td><td>
</td><td>
</td></tr>
<tr><td>(b) M1 – SE.BD
</td><td>
</td><td>
</td></tr>
<tr><td>(c) M2 – SC.L
</td><td>
</td><td>
</td></tr>
</table>

Table 8.5 shows the concrete roofs in M1 and M2. Their behaviour was the opposite of the traditional houses; as the day progressed, they got hotter. This is because they store heat in their thermal mass, which takes time to release back into the air at night. This is due to the concrete's thermal lag, which is a delayed peak in internal temperatures compared to external ones. However, the concrete roofs did not get as hot as the iron roofs due to their lower decrement factor. A lower decrement factor means that the peak internal temperatures should be less than the peak external temperatures compared to the drop created by the corrugated iron roof. Concrete roofs have a decrement of 0.74, compared to 0.98 for irons roofs. This is not only due to the material's thermal conductivity but also its thickness; the concrete roof is 200mm compared to 5mm, which is the thickest corrugated iron. The temperature increase throughout the day was inconsistent; shaded roof areas were not as hot as exposed ones.

This difference increased as the day progressed. The concrete roof in figure (a) is half-shaded by construction on the upper floor. A sample point in the exposed part was 29.4ºC at noon but heated up to 36ºC by sunset. The shaded area also warmed but to a much smaller extent, going from 27.2ºC to 28.6ºC. This emphasises the significant impact shading has on concrete slabs.

In case M2, the increase was minor, going from 30.6ºC to 32ºC. Though their roof was also exposed, it had thick white marble tiles that could have reflected the sunlight and provided additional thermal mass. White marble can reach a Solar reflectance index of 90 when polished, while rough concrete tiles measure between 40-50 (Rosso et al., 2016). A higher reflectance index is preferred in hot urban climates to reduce the urban heat island effect.

Air temperatures

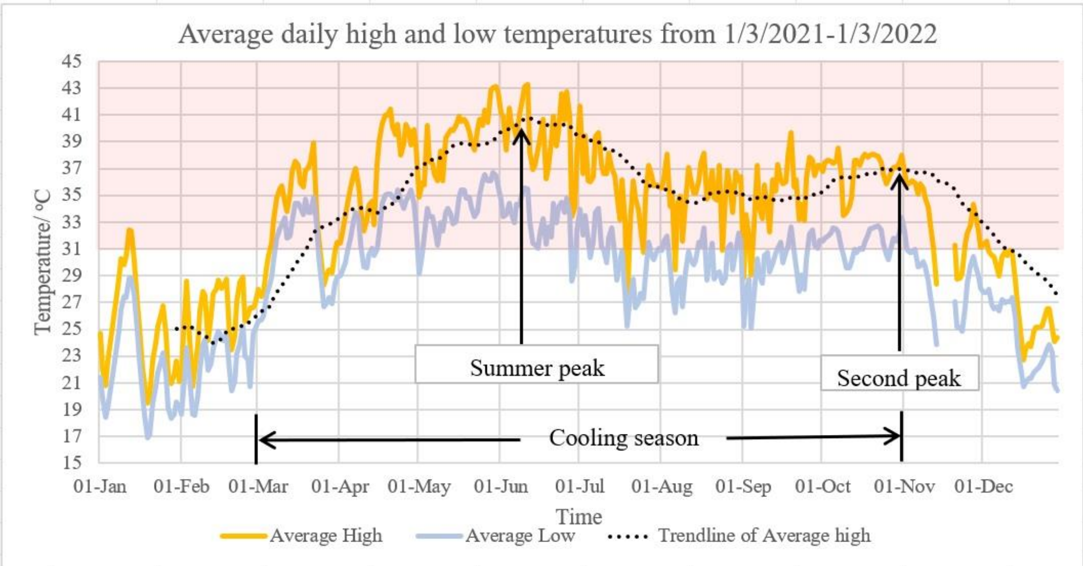


Figure 8.11 The average outdoor daily high and low temperatures from 1/3/2020-1/3/2021

This section focuses on the internal air temperatures in the 4 case study buildings. The outdoor data logger installed in the balcony of M1, recorded the temperatures throughout the monitoring period. They reflect the local microclimate conditions, which will likely be hotter than the temperatures reported by the weather station due to the heat island effect. The maximum recorded temperature was 52ºC at 31/05/2021, which is the peak summer period. It extends from May to July as shown in Figure 8.11, where even night time averages were above comfort levels, which highlights the necessity of mechanical cooling. It is followed by the slightly cooler rainy season, and then a second peak from

October to Mid November. The cooling season was defined as the period when the outdoor temperatures exceeded the comfort temperature of 30.9ºC. This was an 8-month period from April to October. November was a transitional month with around 40-50% of days exceeding the limit during the day, therefore it was excluded.

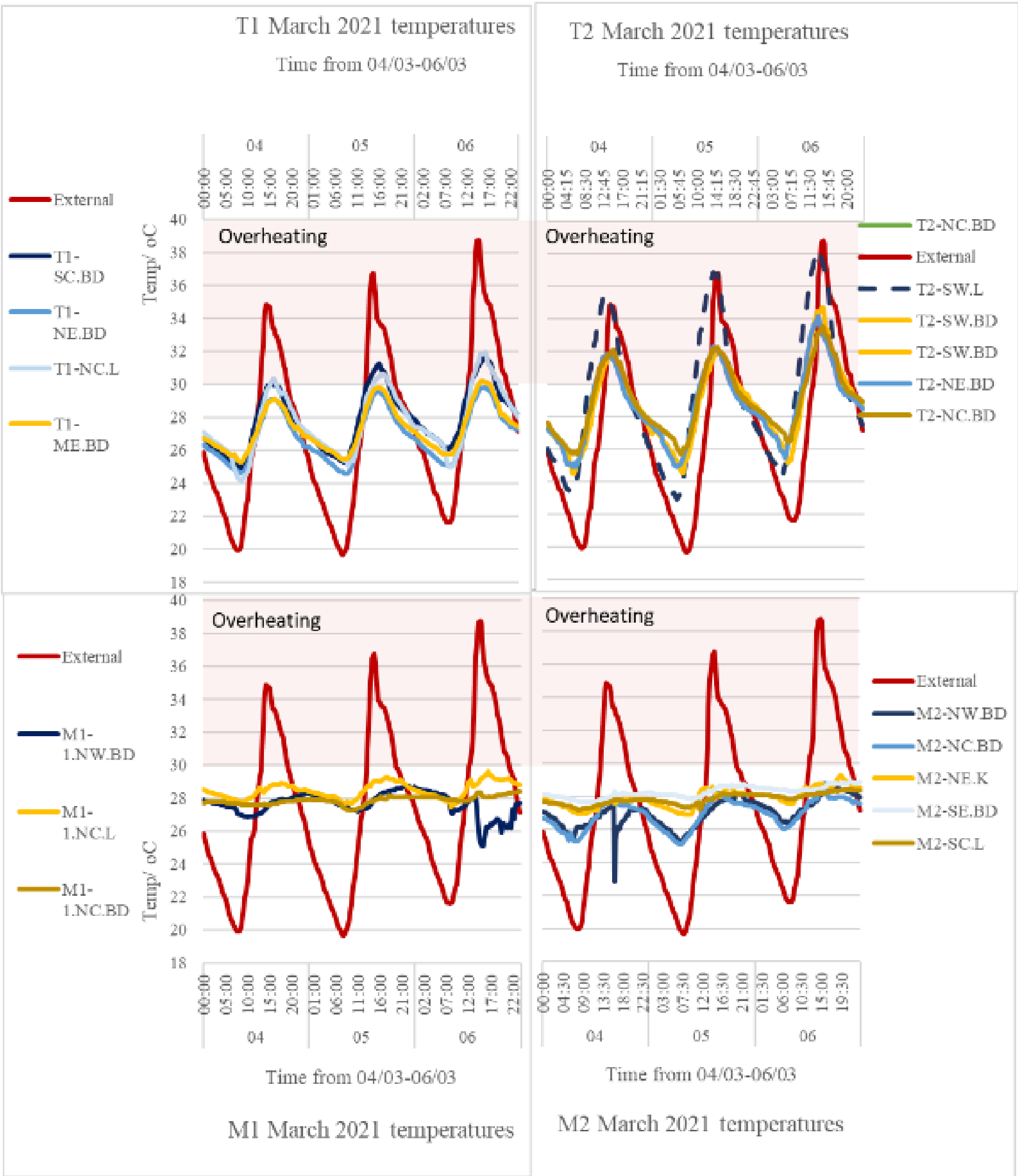


Figure 8.12 The thermal performance of T1,T2,M1 and M2 when the AC was turned off in early March

Internal air temperatures are highly influenced by the AC. Therefore, to isolate the impact of the building's fabric, this section will assess air temperatures using monitoring data collected in early March

2021, before the ACs were turned on. This will then be explored during a sample week in the hot season in section 8.4, as the additional heat stress may reveal new patterns.

Figure 8.12 shows the performance of four buildings in three sampled days. The AC was turned on briefly in M1 and M2, reflected by the sudden drop in the blue lines. Otherwise, the buildings were free running. In line with the patterns revealed by the thermal imaging, traditional buildings T1 and T2, which have iron roofs, exhibited a significant internal diurnal swing reaching 7-9K compared to just 2-3K in the modern buildings M1 and M2. There was no overheating in the modern buildings, while the traditional ones overheated between 2-4K. The veranda SW.L was drawn in a dotted line because it had a different construction; both the walls and roofs were corrugated iron. The space heated up as much as the outdoors but was cooler than the other spaces at night. It was not as cool as the outdoors as it received warmth from the brick walls of adjacent buildings. T1 performed better than T2 by around 2K, an important fact that will be revisited in section 8.5 during the cooling season.

The modern buildings achieved a thermal lag between 2-7 hours, while no lag existed in the traditional ones. This contradicts the internal diurnal pattern shown in Figure 8.9, which shows the traditional buildings being coolest around noon.

The impact of orientation was less pronounced during this cooler period. Most spaces in each household had a similar range of temperatures, suggesting that the building fabric has a more considerable impact on the internal temperatures. The only significant impact of orientation was observed in case M2, where northern spaces were 2K cooler than southern ones. As the air temperatures and solar radiation increase in the summer, the variation due to orientation might increase. However, this is difficult to measure due to the ACs being turned on in some spaces and not others.

8.4.The impact of the AC on thermal conditions

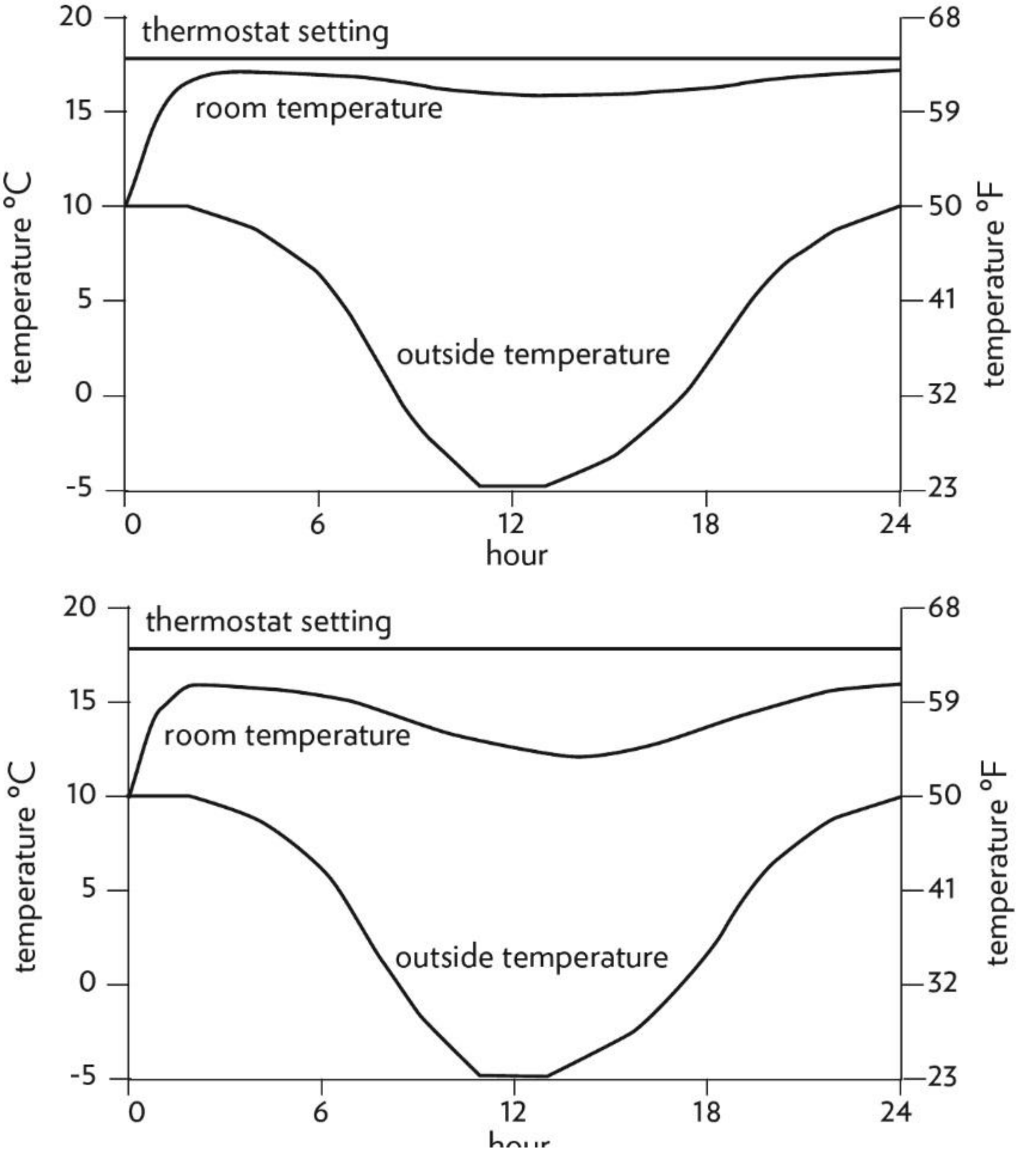


Figure 8.13 The performance difference when heating a well-insulated room (top) versus a leaky room (bottom). Source: (Meadows, 2009)

The relationship between the building fabric and HVAC systems is explained in the book 'thinking in systems' (Meadows, 2009). She theorises that most processes are not linear, but rather part of a feedback loop. One particular type of loop is the balancing or goal seeking loop, where the system tries to reach stability and equilibrium. An example of this is a how, over time, a hot cup of coffee becomes cool yet an iced coffee warms up, they are both trying to reach room temperature. Similar to the coffee cup, Meadows explained that temperatures inside the building are constantly trying to reach outdoor temperatures. Adding active cooling or heating creates an additional ‘loop’, this is why when a furnace warms up a room, temperatures do not just rise steadily. These two balancing loops compete; the furnace tries to heat the room to the desired temperature, while the heat leaks out through the building fabric as it attempts to reach equilibrium with outdoor temperatures. The room is only sufficiently warmed if the ‘furnace loop’ overpowers the 'leak loop’. This can be aided by weakening the 'leak loop’ by improving the building fabric or reducing the difference between the outdoor and desired indoor temperatures. Figure 8.13 reflects the two loops by illustrating how a room warms up in a leaky and well-insulated house. Firstly, the well-insulated room almost reaches the thermostat setting, whereas the leaky one does not. Then as outdoor temperatures drop and the pressure difference between outdoor and indoor temperatures increase, the poor performance accelerates in the leaky room, while the insulated only drops slightly. A similar process happens when you try to cool a room with an AC. The key difference is the reversed flow as heat infiltrates the building rather than leaking out because it is hotter outdoors than indoors.

With evaporative coolers, humidity creates a third loop, adding further complexity. When an evaporative cooler is turned on, it increases the room's humidity and drops the temperature. This momentum decreases as the room becomes saturated and humidity exceeds 60-70%, which is the humidity of the air coming out of the AC in hot-dry climates (Xuan et al., 2012). The humid air needs to be released outside, and new fresh air is introduced. This fresh air is hot outdoor air that needs to be cooled. If the building fabric works well, the evaporative cooler does not need to be turned on for long to cool the room, which reduces the chances of reaching that saturation point and needing outdoor air.

To map these relationships in the case study buildings, this section looks at two sampled rooms in each building during the hottest period of the year from the 23rd to the 28th of May. Each graph shows the external temperatures, the internal temperature in the conditioned room, the humidity, the period the AC was on, and power cuts. An unconditioned room was also added for reference to compare with. The unconditioned room would reflect the 'leak loop', which can be assumed to be the same in the conditioned room. Therefore it becomes easier to see the performance of the HVAC loop. Any variations in the two sampled room's size or building material will be highlighted to theorise on its impact on the AC efficiency.

In addition to the detailed week sample, this section will look at the overall AC efficiency throughout the peak AC usage period from May to July. This is done through a comparison between the average temperature difference between the conditioned and unconditioned space when the AC was on. For example, assuming the outdoor temperature is 40°C and the internal temperature in one building is 35°C and 30°C in the other, due to building fabric differences. If after turning the AC on they both became 25°C, comparing with the outdoor temperatures wouldn't be representative as one managed to achieve a 10K difference while the other dropped 5K. As the initial data showed the differences between the rooms was small, the difference is most likely caused by the AC more than the orientation.

The AC analysis of the case study T1

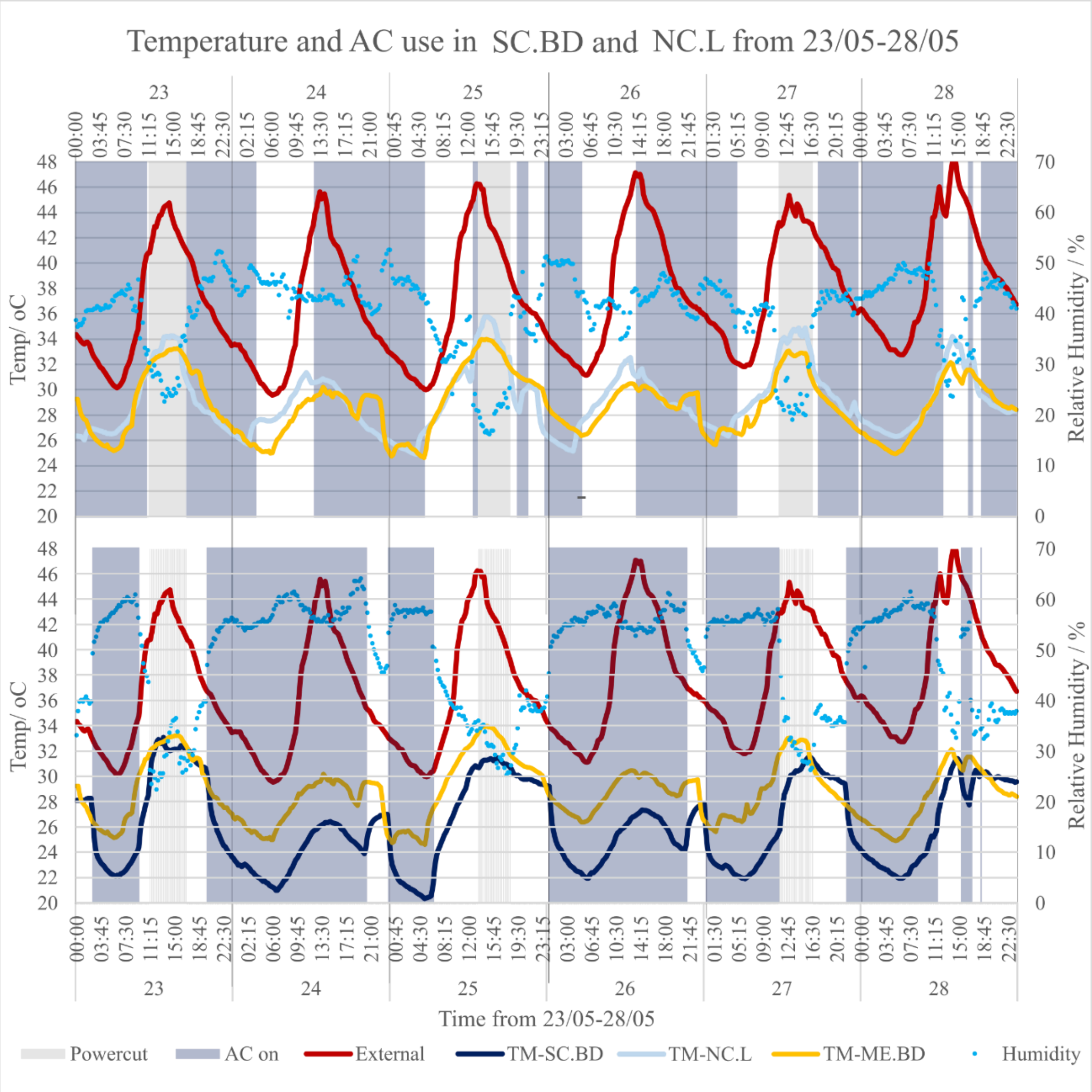


Figure 8.14 A graph showing the temperatures and AC use in SC.BD and NC.L from 23/05 till 28/05

In T1, bedroom SC.BD has an area of 17 sqm and thick stone walls, while the living room NC.L has an area of 40 sqm and typical brick walls, yet they both have one evaporative cooler. Figure 8.14 shows the temperature, humidity and AC use of the two spaces compared to the unconditioned bedroom ME.BD, which got some coolth from the opening linking it to SC.BD. So it cannot be considered entirely unconditioned. Both NC.L and SC.BD had minimal thermal lag, with the internal peaks matching the external ones. However, the combined AC and building fabric performance created a drop that reached up to 20k from the outdoor temperatures.

Figure 8.15 The key plan for T1

The evaporative cooler in NC.L created a thermal profile similar to unconditioned ME.BD. This meant that with extensive AC use, the internal diurnal swing ranged from 25 to 36°C, with humidity levels averaging 45%. When comparing the 24th with the 25th of May, which had similar outdoor temperatures, the internal peak reached 31°C when there was extensive AC use and 36°C when there was minimal AC use. It should be noted that the data logger was in the centre of the room while the AC was on the north end. The temperatures were likely cooler on the sitting area near the AC. Using the CBE Thermal Comfort Tool, the maximum comfortable temperature at 45-65% humidity is around 26-27°C, based on the PMV method in the ASHRAE 55. This explains the residents' complaints of discomfort. The temperatures in the bedroom ME.BD and living room NC.L only remained within that level for a few hours at night, while the humidity only dropped when the AC was turned off.

In the smaller bedroom SC.BD, the AC managed to keep a much cooler internal diurnal swing from 20-32°C. The high thermal mass is also a likely contributor as the internal peak on the 25th of may (unconditioned day) was only 32°C compared to the 36°C in the living room NC.L. This compares to a peak of 26-27°C on the AC extensive days of 24/05 and 25/05. The room also retained coolth, taking 4.5 hours to heat up from 26 to 32°C (the unconditioned room status) when the AC was turned off on 27/05. However, it exceeded the comfort temperature of 30.9°C within 2 hours. The AC was also used extensively in this space, reaching 27 consecutive hours. The humidity levels were higher, reaching 65% and dropping only when the AC was turned off for a long time, which only happened around power cuts. When the AC was turned back on, it took an hour to increase from 15 to 50%. These findings suggest that an evaporative cooler is likely to perform better in a smaller room with higher thermal mass at the cost of higher humidity levels.

Throughout the summer, the evaporative cooler, on average, cooled 0.8K during the day and 1.2K at night. The maximum it achieved was 6.3K drop during the day and 6.6K at night. The evaporative cooler caused erratic drops in temperature. This could be because the pump needs to rewet the straw every few hours, creating increases and drops in temperature. This was seen in T1, T2 and M2, which all have evaporative coolers.

The AC analysis of the case study T2

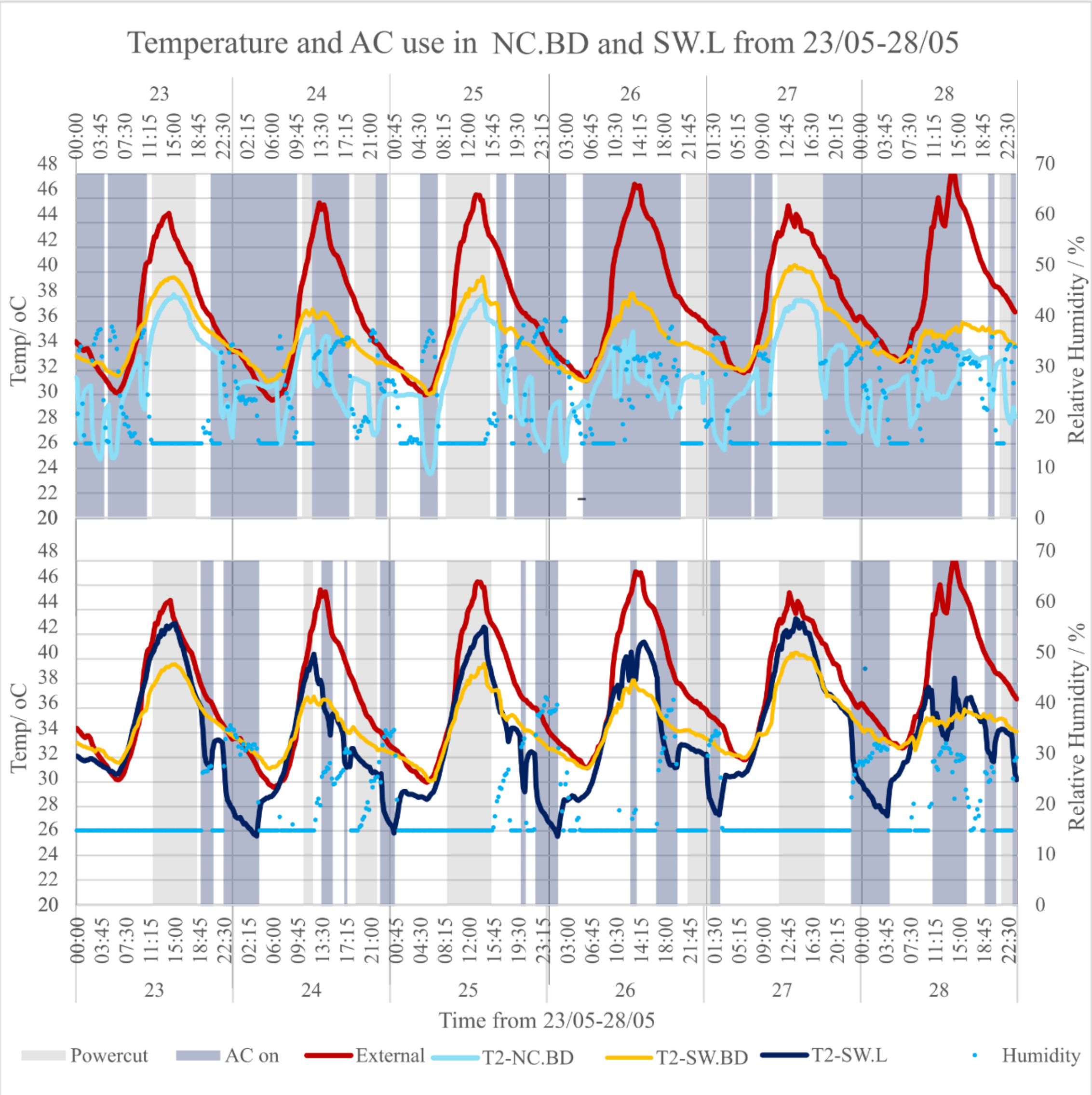


Figure 8.16 A graph showing the temperatures and AC use in T2-NC.BD and T2-NW.BD from 23/05-28/05

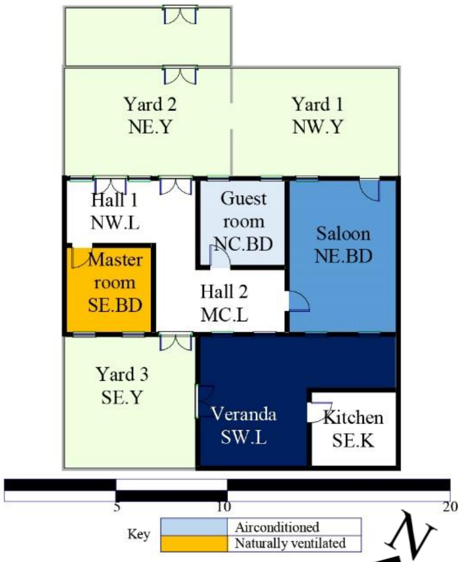


Figure 8.17 The key plan for T2

In T2, the bedroom NC.BD had an area of 14 sqm and a false ceiling compared to the living room SW.L, which had an area of 28 m^2 and a metal roof. The thermal conditions in T2 were a more extreme variant of the conditions in T1, as shown in Figure 8.16. The internal diurnal swing was larger, ranging from 24-38°C in the false ceiling bedrooms NC.BD and SW.BD and 26-42°C in the metal roof living room SW.L.

The spaces NC.L and SW.BD in T1 has the same structure as the bedrooms NC.BD and SW.BD in T2. To assess the performance of the fabric without the AC, the temperatures can be compared on the 25th of March, when the AC did not work in both houses. T1 peaked to 34-36ºC compared to 38-40ºC in T2. This means that the evaporative cooler in T2 has to reduce an additional 4K than it does in T1. This could be due to specifications, material condition, air infiltration levels, or volume differences. The AC was used for 16 hours in the bedroom NC.BD (Top part of Figure 8.16) on the 26th of May, which reduced the internal peak from 38 to 35ºC (compared to SW.BD), with an RH level of 35%. This is compared to 30-32ºC at the same time in T1, which is a 6-7K difference. On the 27th of May, when the AC was turned off, the temperatures increased from 27ºC to 33ºC, the same level as the unconditioned space, within 1.5 hours. This shows that the fabric does not retain the coolth.

This is further exacerbated in the living room SW.L, which uses the AC infrequently and has a hotter roof. During the day, temperatures in SW.L would reach 43ºC, dropping to the levels in the unconditioned room SW.BD when the AC was on, as evident on 28/05.. However, at night, the evaporative cooler achieved a significant drop (5-6K), even when turned on for brief periods, as seen on 23/05 and 26/05. This is likely because the metal roof's direct radiation into the night sky helped reduce the cooling load quickly. This indicates that a lightweight space can easily achieve night comfort with minimal AC hours. Figure 8.18 shows the walls and windows in the living room SW.L, and it is evident that it is well-ventilated from all the openings, which is why the humidity levels never rose above 40%.

Over the entire season, the maximum drop caused by the evaporative cooler in house T2 was 7.6K during the day and 7.8K at night. The average was 2.8K and 3.3K, respectively. The orientation difference between the northern room NC.BD led to a 1K drop in temperatures compared to the southern room SW.BD, which is the same size. This is smaller than the drops the building fabric and AC differences achieved.

Figure 8.18 A photo of the living room SW.L walls and roof and evaporative cooler

The AC analysis of the case study M1

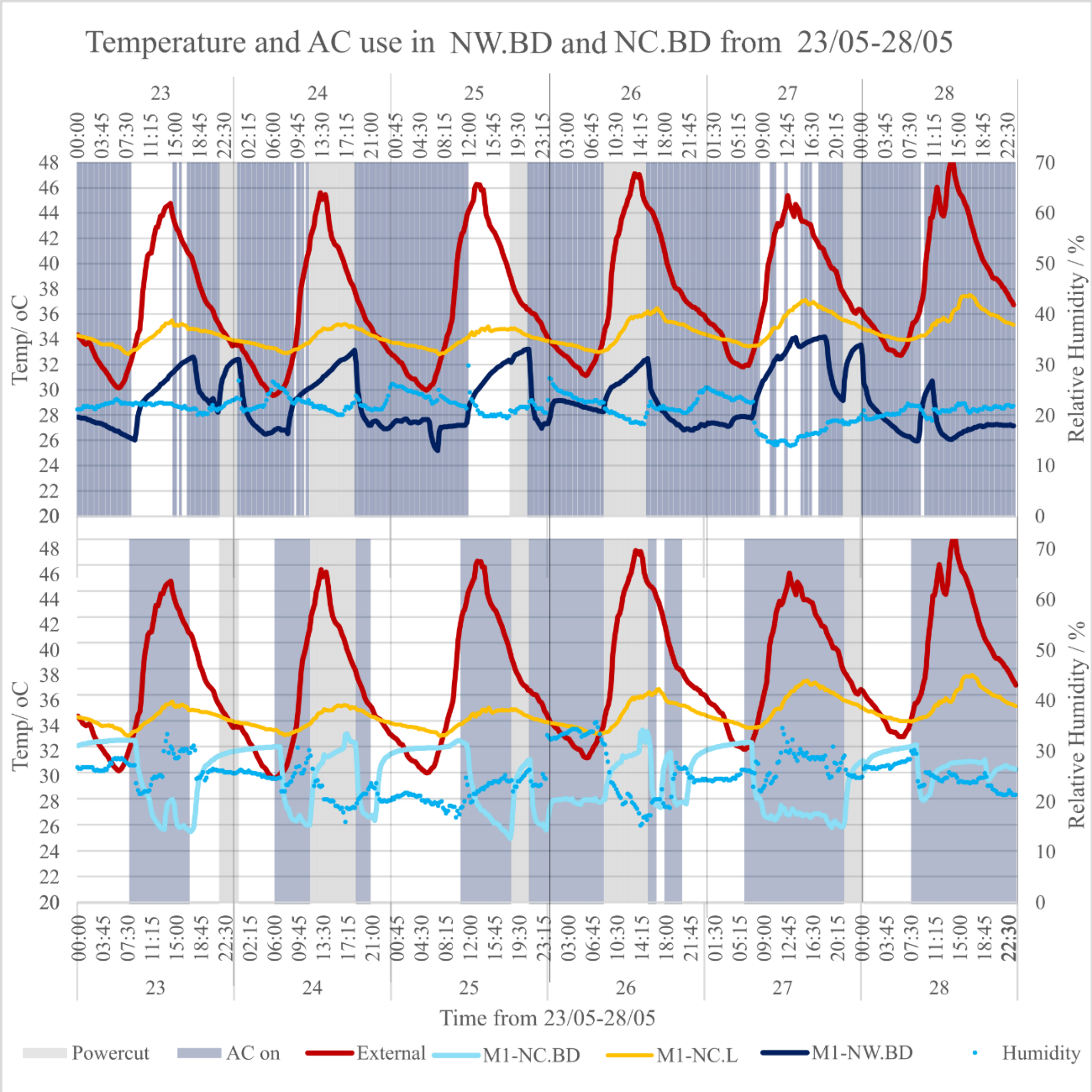


Figure 8.19 A graph showing the temperatures and AC use in M1-NW.BD and M1-NC.BD from 23/05-28/05

The modern house M1 had the same construction throughout the three sampled spaces. However, the living room NC.L and bedroom NW.BD are only half shaded in the roof, while the bedroom NC.BD is fully shaded. The bedrooms NC.BD and NW.BD are both 30 m^2. The refrigerant AC kept the relative humidity levels remained low, between 10-25%, meaning that discomfort from excessive humidity was minimal.

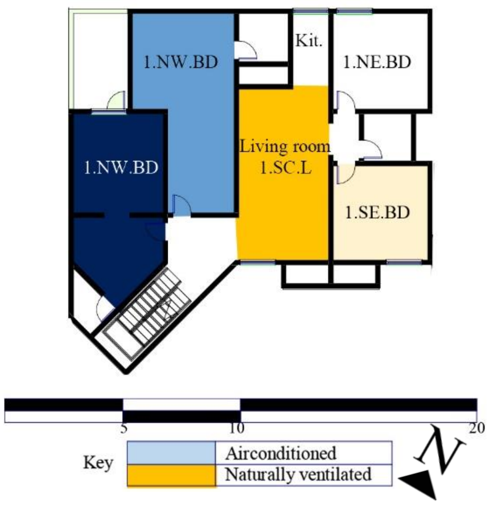


Figure 8.20 The key plan for M1

The unconditioned living room 1.NC.L was the reference. Figure 8.19 shows that it usually only had a 4k diurnal swing which slowly increased, depending on external conditions, till it reached 34-38ºC at its hottest on 28/05. Comparing this profile to the bedroom SC.BD in T1, which had a high thermal mass wall but a lightweight roof, it can be noticed that SC.BD could cool to lower temperatures at night due to the roof.

The AC was used extensively. Looking at bedroom NW.BD in the top part of Figure 8.19 shows that on the 25th, the AC achieved a 6K drop in less than two hours, after which it stayed stable at 27ºC (the set point) until a drop in outside temperatures helped it reach 25ºC. After the AC was turned off at noon, the temperatures rose sharply from 27ºC to 30ºC in an hour before slowly reaching 34ºC like NC.L within 10 hours. This means that the room was only within the comfort temperature of 30.9ºC for 2 hours after the AC was turned off, this was 5 hours on the 23rd and 3 hours on the 26th. On the 27th, as the AC was not turned on for enough time to reach 27ºC, it reached 34ºC in 3 hours. This signifies that the approach the users decided to adopt by cooling up to 18ºC could be efficient if the AC were turned on for a few hours prior.

An AC was installed in bedroom NC.BD on 07/04/2021, halfway through the monitoring period. The sampled period at the bottom of Figure 8.19 shows that the AC was used midday, as discussed in section 7.2.4. The AC could cool the room from 32ºC to 26ºC (the setpoint) within 2-3 hours. After the AC was turned off, the room would go back to 30.9ºC within 2 hours before reaching 32ºC within 4 hours and remaining at that level until the AC was turned on again, the longest being 15 hours. The humidity was slightly higher, reaching 35%, this is probably moisture coming from the ensuite bathroom. Overall, NC.BD is the most shaded and cool room in the house. It remains stable, whereas NW. BD's temperature keeps rising until the AC is turned on again. The findings in M1 suggest that though the high thermal mass in concrete rooms leads to a high cooling load at night, they cool relatively quickly with a refrigerant AC and retain that coolth within comfort for 2 to 3 hours. If the room is well-shaded, the room will stay below 32ºC, which would be warm but not hot. The refrigerant AC on average cooled 6K during the day and 5.9K at night. The maximum it achieved was an 11.5K drop during the day and 10.5K at night. This drop was the highest in all four recorded case studies.

The AC analysis of the case study M2

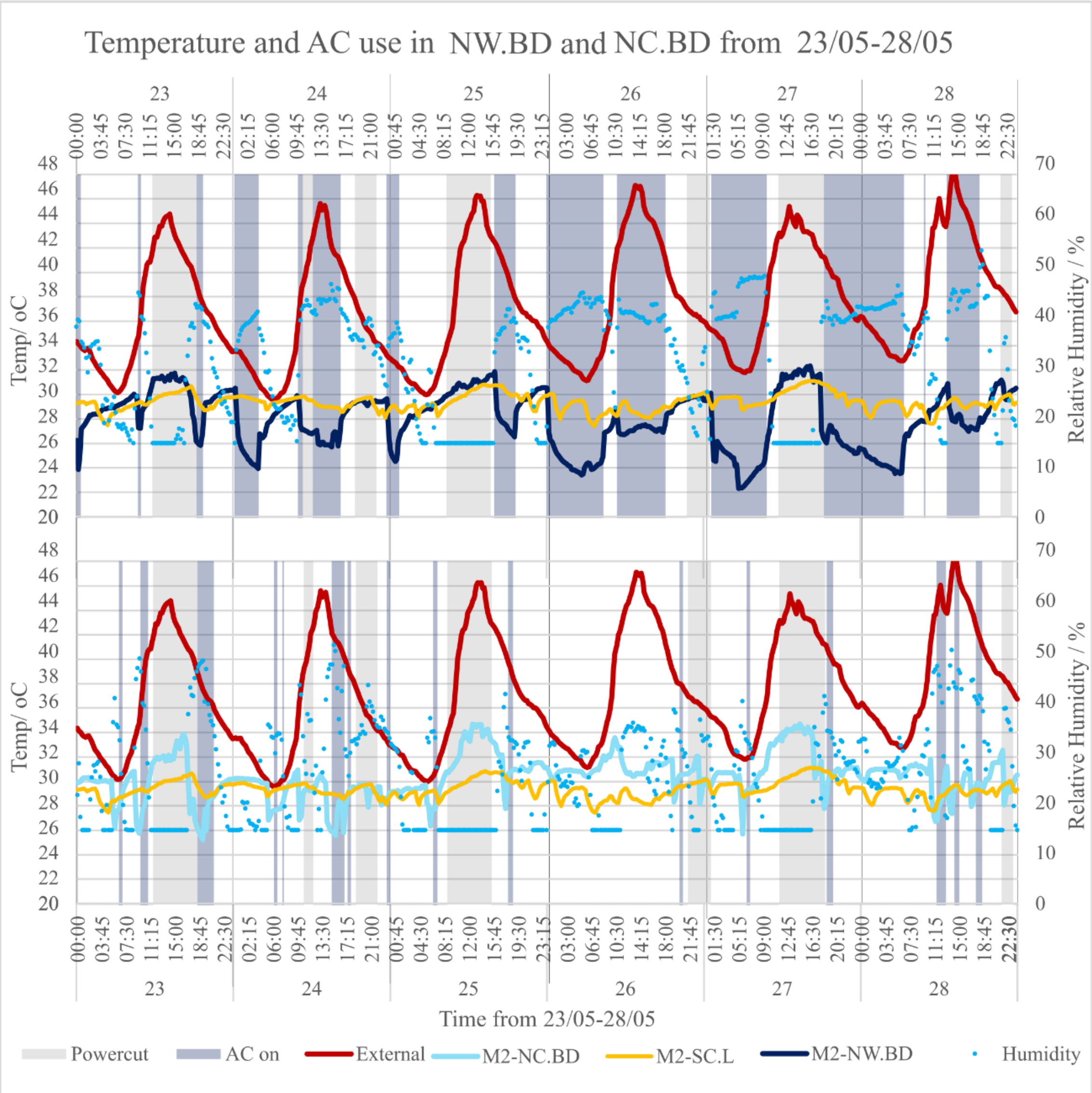


Figure 8.21 A graph showing the temperature and AC usage between 23/05-28/05 for M2- 1.NW.BD and M2-NC.BD

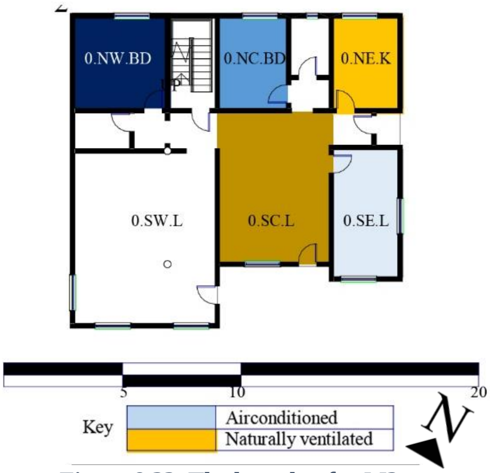


Figure 8.22 The key plan for M2

M2 provides an interesting contrast because it has the same construction as M1 but uses evaporative coolers instead. However, the humidity levels rarely exceeded 45%.

The living room SC.L was used as the reference; a balcony shades its southern façade, and another floor shades its roof. Because of this, its 4K diurnal swing was much lower than the living room NC.L in M1, staying at 28-30°C throughout

28/05. This is a further testament to the high performance of high thermal mass rooms when well-shaded, similar to the performance of bedroom NC.BD in M1.

The two bedrooms that were monitored were used in different ways. The bedroom NW.BD was used by the boys, who frequently turned the AC on. Figure 8.21 shows that their usage is irregular on days like 24/05 and 25/05, where they used the AC midday and on days like 27/05 where they used the AC at night and in the evenings. This is probably impacted by power cuts and when the room is occupied, which changes daily. On 26/05, the AC helped reduce the temperatures from 30ºC to 26 ºC within an hour, then slowly to 24ºC within 4 hours. The humidity would reach 45%, which would be comfortable at cool temperatures. The evaporative cooler was efficient because the indoor temperatures rarely exceeded 30ºC despite reaching 46ºC outside.

The female user in bedroom NC.BD used the AC infrequently, which is why the temperatures in her room were similar to SC.L, as shown at the bottom part of Figure 8.21. From 25/05 to 28/05 it was hotter in this room than it was in the unconditioned spaces, due to the exposed wall in the north. On 23/05, the evaporative cooler reduced from 32 to 26oC in one hour, to 24ºC after four hours.

Overall, the evaporative cooler on average cooled on average 3.3ºC during the day and 4ºC at night. The maximum it achieved was 10.7K drop during the day and 9.98K at night. Which is significantly more efficient that T1, despite using the AC for less hours as revealed in section 7.3.

8.5. The symbiosis of Air conditioners and the building

The building fabric's ability to keep the heat out but also work efficiently in combination with air conditioner varies throughout the year, depending on the outdoor weather. To illustrate this, Figure 8.23 maps the average overheating that occurred from March to October, which is the cooling season as established by section 8.3. The two graphs show the length of the overheating period, intensity and time of occurrence. It also shows the average number of hours the AC was on for each space, indicated by the blue numbers. This is to help understand how much the AC contributed to reducing the overheating.

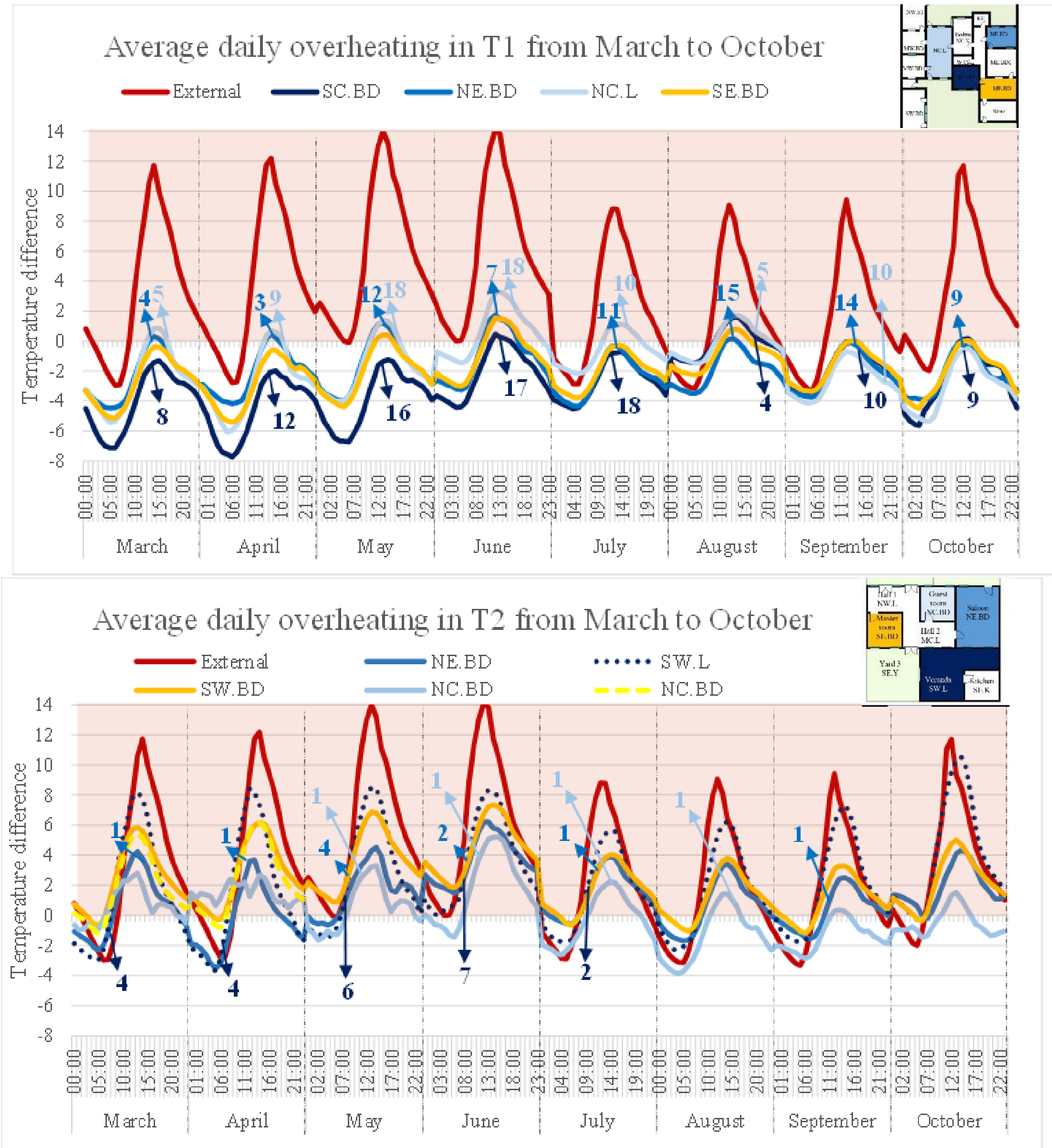


Figure 8.23 Overheating in T1 and T2 from March to October 2021. Note: the blue numbers are average daily AC hours for that month in the spaces

Figure 8.23 shows the overheating in T1 and T2. For T1, the worst month was June. In this period, NC.L was, on average, 3k hotter than comfort, with the overheating period reaching 13 hours from 7:00-20:00. For ME.BD and NE.BD, this was reduced to 8 hours 9:00-17:00. August also had an average of 12 hours of overheating in two bedrooms SC.BD and ME.BD. The internal overheating in August was similar or more than in July, September and October, which is also the case for T2 and M2 as shown in Figure 8.23 and Figure 8.24 respectively. This is Interesting because the outdoor temperatures in August are actually lower than these months as shown in Figure 8.11. This is most likely because humidity is high in August which hinders the efficiency of the installed evaporative coolers. This is especially true for spaces that used the AC the most T1-SC.BD and T1-NC.L. Cross referencing these overheating periods with the occupants' usage patterns discussed in chapter 7 shows that the users would most likely be at work or school at the beginning of this overheating period and would be most affected by the period from 15:00-20:00. This means that design solutions for T1 should target that, at the minimum, they are able to achieve comfort during this design extreme.

T2 struggled with overheating in both extensiveness and severity. The overheating period included all 8 months with most spaces overheating all day and night. The overheating reached an average of 10K in October, where the external temperatures exceeded the internal ones in the closed veranda SW.L, that has the corrugated iron roof. This means that the internal air temperature was 41ºC on average.

When we look at the average AC hours, we can see that the extensive AC use in T1 has contributed to its better performance than T2. As mentioned in section 8.3.2, the difference in performance when the AC was not a factor was only 2-4K, whereas it is 6-7K when the AC was turn on (excluding SW.L).

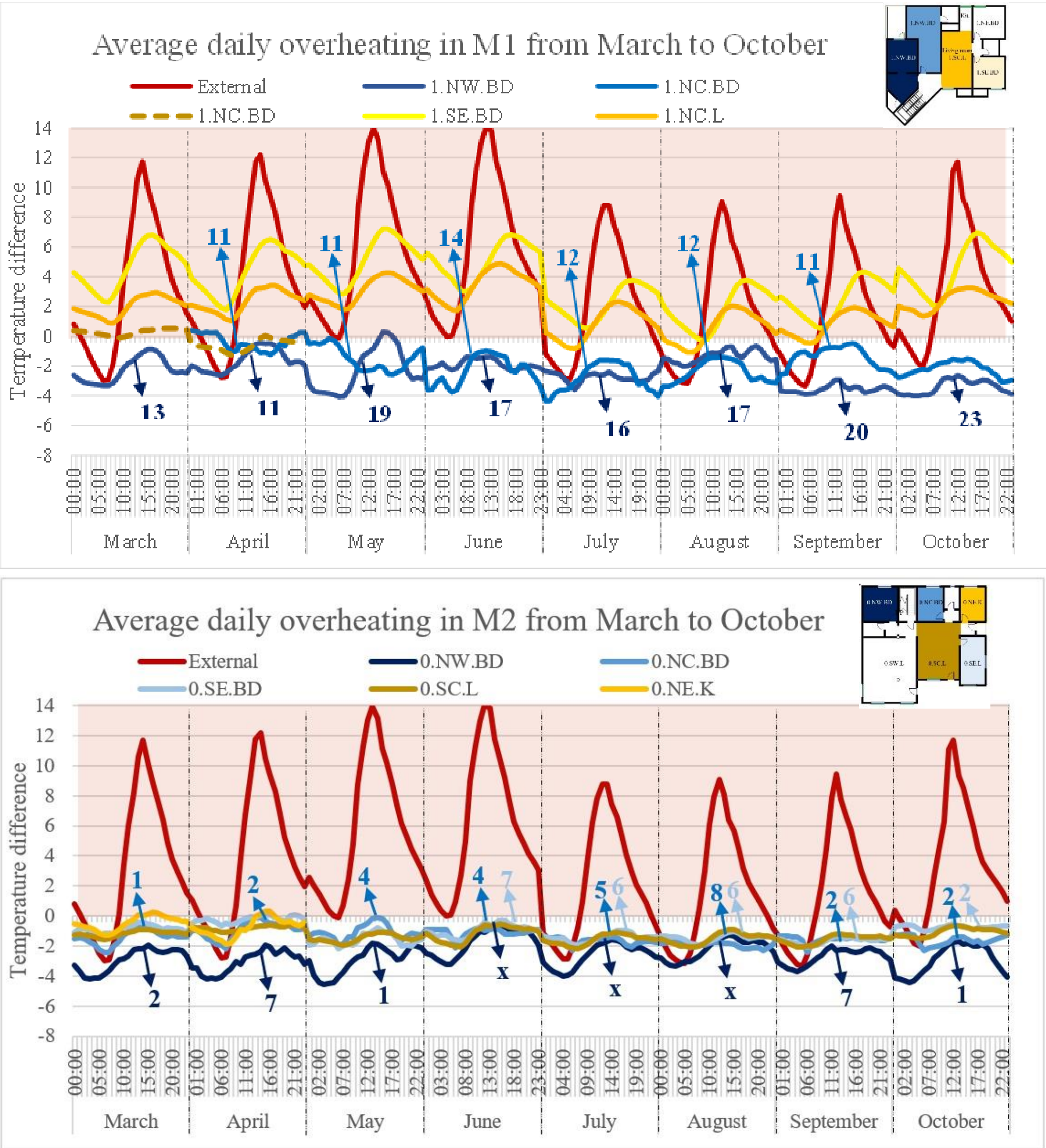


Figure 8.24 Overheating in M1 and M2 from March to October 2021 Note: the blue numbers are average daily AC hours for that month in the spaces

The annual overheating pattern in the modern buildings shows that M2 maintained the cool temperatures seen in section 8.4 with minimal AC for the rest of the year. The internal temperatures remained stable both day and night with a 2k variation. M1, however did not perform as well. The conditioned spaces didn't experience overheating, but the AC was used extensively for 11-23 hours daily. The unconditioned spaces however experienced overheating both day and night reaching 7K in April, May and June. The bedroom NC.BD (shown in dotted line) was unconditioned in March and half of April, but was then conditioned from then on. It didn't experience significant overheating even before the AC was installed as it was north facing and the roof was shaded.

In May, the unconditioned bedroom SE.BD was added to the study and showed that it had a larger thermal range than the rest of the house. This is most likely because it has an exposed roof and southern wall, whereas the other rooms either have a shaded roof or are north facing. The excessive heat absorbed during the day meant that the temperatures only cooled to 34°C at night, it has the hottest night-time temperatures in all of the 5 houses. The occupant only uses it in the winter because of this as mentioned in section 6.5. The other two spaces NC.L and SE.BD had exposed southern windows and exposed roofs. This highlights that concrete buildings have the potential to be cool, if they are shaded well. This is further emphasised by the thermal images taken in section 8.3 that showed the half shaded concrete roofs. They also have the potential to be excessively hot both day and night if when exposed.

8.6. Additional Problem areas

Section 8.3.1 focused on the thermal images of the roofs of our case study buildings. However, the images were taken for all the spaces in the case study buildings, including the walls, windows and doors. The images revealed additional sources for heat infiltration from the outdoor environment that will be explored in this section. The first part will focus on issues attributed to poor maintenance or construction while the second will focus on windows and doors.

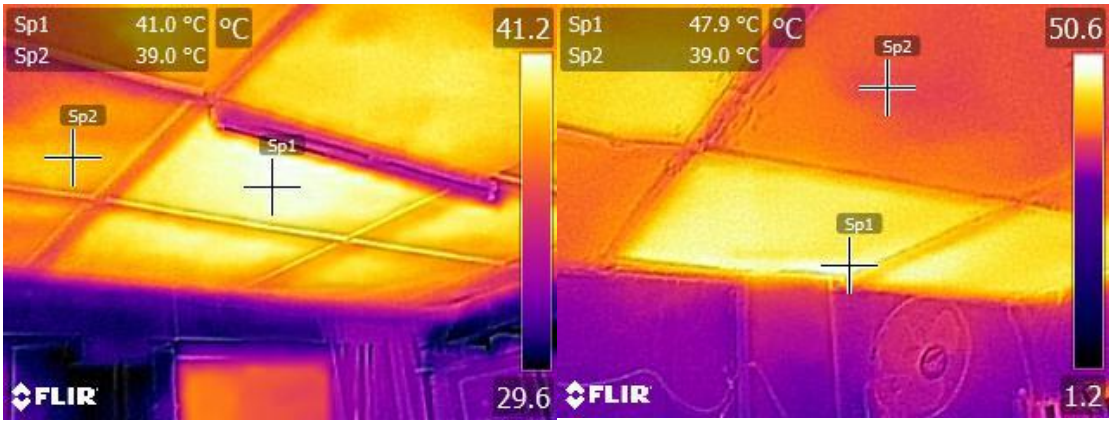


Figure 8.25 (Right) A thermal image of the false ceiling in the kitchen T1-NC.K.1 showing different thermal profiles in each square. (Left) The false ceiling in bedroom T1-NE.BD showing less discrepancy between tiles.

T1 is an old building, as such, many of its building components are not in a good condition. The first problem that was evident was the false ceiling. Patches of it (as shown in Figure 8.25) had different thermal properties in the kitchen NC.K.1, with some reaching 47.5°C while others 39°C. In the bedroom NE.BD, the discrepancy is smaller at only 3 K difference. Interestingly, they both shared the same lower limit (39ºC) despite some tiles being significantly hotter in the kitchen. Poor workmanship is therefore the most likely the reason for the discrepancy, as both roofs were constructed at the same time using the same materials.

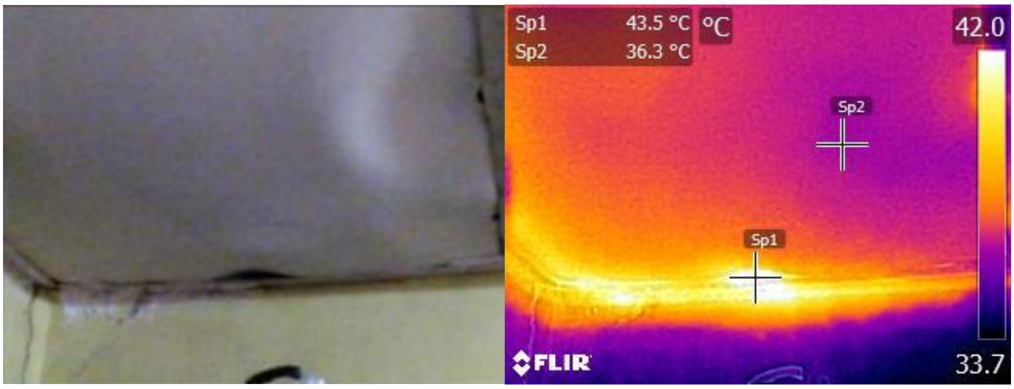


Figure 8.26 A poor connection between wall and false ceiling in the kitchen TM-NC.K.1

Figure 8.26 shows how the poor connection with the wall is leaking heat into the kitchen. This thermal image was taken at 5pm. The centre of the false ceiling had cooled to 36.3ºC while the leaking area was still 43.5ºC.

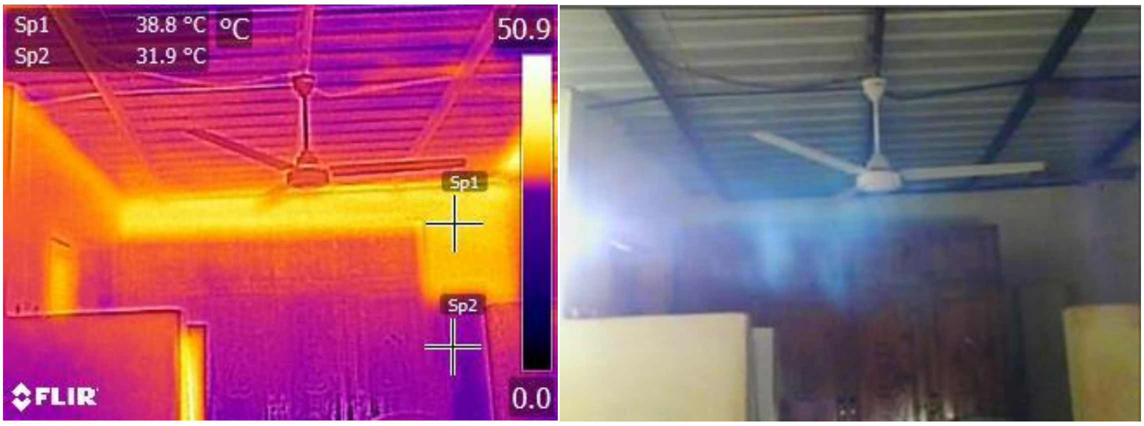
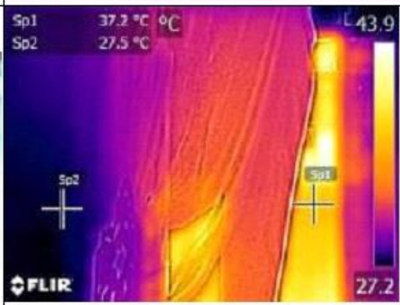
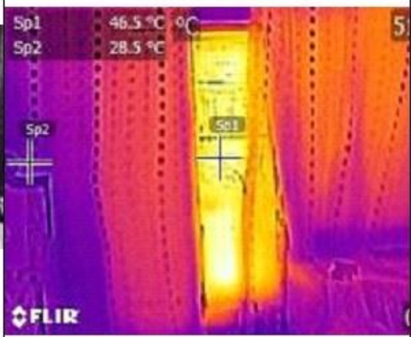
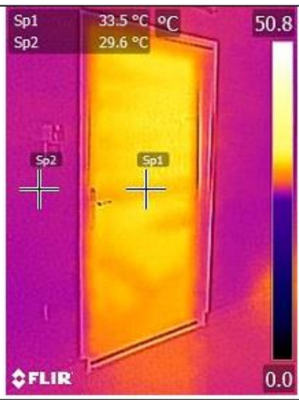
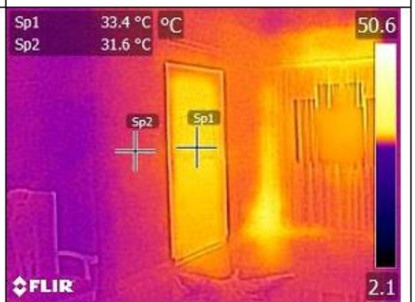


Figure 8.27 (Left): an image of the living room T3-MW.L. (Right): a thermal image of T3-MW.L taken at 5:00 pm

In the living room T3-MW.L, the upper half of back wall was a plaster on mesh extension to the brick wall causing heat build-up. When comparing the points sp1 (38.8ºC) and sp2 (31.9ºC) the difference is 6.9K.

Doors and windows

Table 8.6 Thermal images of the doors in T1,T2,T3 and M2

<table>
<tr><th>Space</th><th>Noon</th><th>Sunset</th></tr>
<tr><td>(a)T1-NC.L Metal
</td><td>
</td><td>
</td></tr>
<tr><td>(b)T2-SC.L Metal
</td><td>
</td><td></td></tr>
<tr><td>(c)T3-SE.L Metal
</td><td>
</td><td>
</td></tr>
<tr><td>(d) M2 – SC.L
Composite
</td><td>
</td><td>
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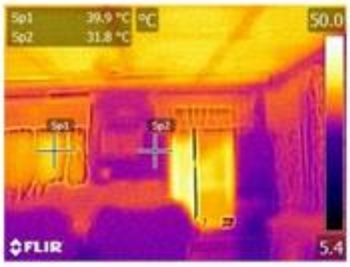
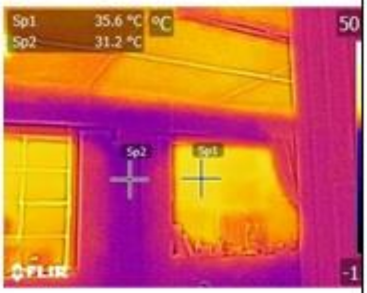
The composite door shown in Table 8.6(d) performed better than the metal doors found in all the other case study buildings. During noon, it was 4K hotter than the wall compared to 10-18K for the metal doors in the traditional houses. This could be a contributor to the cooler temperatures in M2. As the metal doors cooled by sunset this difference reduced to 2-6K.

Table 8.7 Thermal images of Windows in T1.T2, T3, M1 and M2

Windows	Noon	Sunset
(a)T1-NC.L Metal South facing 		
(b) T1 – NE.BD Metal North facing 		
(d)T2-NW.L Metal North facing 		
(f) M1 – SE.BD Metal South facing 		
(g) M1 – NE.BD Metal North facing 		

<table>
<tr>
<td>(h) M2 – SC.L Composite South facing
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<td>(j) M2 – NC.BD Composite North facing
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Error! Reference source not found. shows the windows in our case study buildings. Overall, north facing windows got hotter by 5pm compared to noon whereas southern rooms got cooler as the day passed. North facing windows were also cooler with their temperatures usually around 29-34ºC, whereas southern windows ranged from 35-40ºC. Unlike the doors, composite windows performed just as poorly as metal windows, most likely because they both use single panel glazing.

8.7. Conclusion

This chapter has shown that the traditional houses, having been substantially adapted, no longer behave thermally as they did historically. Their thermal lag is minimal, which makes their peak occur midday when it is hot. In the past, the midday siesta was the only time the indoor spaces were cool, but in the current traditional buildings, the AC needs to be turned on during the siesta. When the cooling season peaks, the residents in the traditional buildings T1 and T2 have to choose between bearing the heat or turning the evaporative cooler on for excessive hours. The excessive use of evaporative coolers, however, comes at the cost of both high energy consumption and high humidity levels, which hinder comfort. T2 chose to limit their AC use to cut costs, which lead to extensive overheating throughout the eight months of the monitoring period, both day and night. As the day progressed, the lightweight roofs started to rapidly cool down, which makes the night-time temperatures more bearable in T2 and comfortable in T1.

The traditional buildings also had a higher s/v ratio due to their horizontal expansion, which meant the roofs were exposed to more radiation than the walls. The modern buildings had lower S/V values, and which has likely contributed in their performance. Though both modern buildings performed well in milder weather, the impact of shading becomes evident as the temperatures rise. The well shaded building M2 was able to remain relatively stable despite the large external diurnal swing, even without the AC. The internal peak temperatures were later in the evening, with nights not reaching the cool temperatures seen in the traditional building T1. The evaporative cooler was able to create large drops in temperatures at a lower humidity rate than the levels seen in T1. The AC electric consumption of the house was minimal compared to the other houses. By comparison, M1 showed a large performance difference between shaded and unshaded spaces. The well shaded north facing room performed well even before the installation of the AC. In spaces where the roof was half shaded, the temperature contrast became larger as the day progressed. In the most exposed bedroom SE.BD, temperatures were uncomfortable both day and night at levels higher than any other space in all four case study buildings. The AC was able to create a steep drop in temperatures until the space reached the setpoint temperature in very limited time.

Therefore, this chapter concludes that modified traditional buildings are only naturally comfortable at night, where their cooling load is small, while modern buildings have the potential of being comfortable or hot depending on shading. They are also more easily cooled the AC, retain that coolth for longer, and have a consistent cooling load both day and night.

Chapter 9 Reimagining the Sudanese house through a climatic lens

9.1.Introduction

The first eight chapters of this thesis focused on gaining an understanding of AC reliance as a repercussion of unsustainable development. It used a sociotechnical lens to reveal how the adoption of modernity expressed itself in the building and occupants of houses in Khartoum. This started by navigating how the socioeconomic change affected Sudanese houses in the past, leading to new typologies as the house morphed to suit its occupants' changing expectations. A hybrid approach of literature review and interviews was then used to fill the timeline gap between the last recorded housing studies and the current socioeconomic conditions. This information was then used as a background to understand how five different case studies changed from their construction to their current use as the occupants changed their lifestyles. The following two chapters looked at how the occupants currently use their buildings, how the buildings perform and the energy implications that stem from these factors. This chapter explores how we can reduce the excessive energy consumption impact of this socioeconomic change using architecture as a solution.

As people migrated from the village to the city, the Sudanese house had to transform from rural to traditional to institutional and then contemporary over 120 years, as discussed in Chapter 2. Unlike the Arab gulf, where people's wealth and adoption of modernity matched the building's evolution, people's lifestyles only changed minimally in Sudan up until recently. The transformation from an outdoor to an indoor lifestyle occurred within just 20 years, which put a significant strains on the housing stock's ability to adapt.

In the evolutionary arms race between the buildings and emerging new lifestyles, the traditional Sudanese house, in its current state, cannot cope with the requirements of a modern lifestyle. The occupants no longer live a migratory lifestyle, the building materials are not the same, and the use of yard spaces is diminished and abandoned. Thus, the AC has become an inevitable coping mechanism, a technological expression of change in behaviour and expectation. Even in modern houses, though they performed well when shaded due to their high thermal mass, compact typology and reduced infiltration rates, they were barely at the comfort level. This means they are likely to suffer when temperatures rise due to climate change. This echoes Osman's (2019) findings. He found that the AC is unavoidable when he analysed the expected conditions in Khartoum by 2070 (M. M. Osman & Sevinc, 2019). In its current climate, Khartoum is only comfortable 24.2% of the time, which is expected to drop to 11.7% due to climate change (M. M. Osman & Sevinc, 2019). Using the program climate consultant, Osman quantified the number of hours in a year that different passive solutions, such as shading, can help achieve comfort. Using Osman's approach, the author found that the combination of sun shading, natural ventilation, dehumidification, and night-flushed thermal mass achieves thermal comfort only 47% of the time; this increases to 70% if an indirect evaporative cooler is used. These figures decrease even further during the hot months of May to July. Comfort is only 0.6% of the time, passive solutions only work 3.9% of the time and the indirect evaporative cooler for 55% of the time. For these months, using an AC is unavoidable for 41% of the time in the light of current expectation. Unfortunately, installing an AC and evaporative cooler in the same space is not practical. Thus, if given an alternative, occupants will either suffer due to fuel poverty or make highly consumptive choices, like air conditioning the entire building. They already consume the rates expected of a fully conditioned house while they run in mixed mode. As stated in section 4.3, if full saturation is achieved, Sudan will be the 14th most consumptive country due to its large population and the high number of cooling degree hours.

Chapter 2 emphasised how, especially in Africa, architectural solutions must meet sociocultural needs. The current energy crisis and expected worsening conditions due to climate change require reimagining the Sudanese home through a climatic lens. Though modernity has changed several aspects of Sudanese society, it still has complex social needs such as conformity and privacy. Therefore, it is paramount that innovation is culturally embedded. Innovation familiar to people is also more likely to be accepted (Tripsas, 2009). In Sudan, people often request that architects design houses similar to those they have seen. When asked if she has ever proposed a sustainable solution like a central courtyard design to her clients, architect 2 said, *'anyone who comes -to me- comes with a specific idea; they want their aunt's house or uncle or neighbour. You can only change their opinion in small matters. This is a big change; if I tried to convince them of it, they would likely seek another architect.'*

Building on existing current practices, rather than rejecting them, also reduces the amount of new unknown variables such as material availability, labour skills or likelihood of public acceptance.

Khartoum poses a unique challenge common in urban centres in developing countries. The adoption of modern culture by a select few contrasts with the economic depravity of the country as a whole. This necessitates creating a bespoke solution that allows these occupants to maintain their modern lifestyle while reducing energy consumption using the limited resources available in a developing country. This complicated situation requires a solution that bridges the gap between low-cost passive buildings like one-story mud houses and high-cost technology-reliant buildings. A new typology built upon taking existing practices that socioeconomic drivers formed and altering them to meet climatic purposes. A mixed-mode building with an enhanced building fabric that can both meet passive design requirements and also intelligently incorporate the AC. Hence the name 'optimised mixed-mode building'. This typology needs to be a seamless progression in the evolution of the Sudanese home as it continually responds to the changing needs of occupants, as discussed in chapter 5. The underlying concept of the solution is viewing the building as a mixture of distinct units rather than one homogenous hybrid building, like a chimaera. This allows different parts of the building to meet different requirements simultaneously, thus collectively meeting the occupant's needs. This idea can be used whenever buildings are required to simultaneously meet conflicting needs, whether climatic, social or economic.

Utilising architecture to solve a social problem has precedence in Sudanese history. As discussed in chapter 2, the institutional house's design was research-based and aimed at creating a typology that could, at the time, affordably meet the occupant's complex social needs within a small city plot. Its success made it endure as a solution beyond government-mandated plots from the 1950s till the 2000s. The designer's core idea was making the male and female sections face opposite directions for privacy, which in its simplest forms was just two rooms. However, as discussed in section 2.4, the typology encompassed a wide range of house sizes and classes, which led to several variations. Similarly, the optimised mixed-mode building is an idea that can be adjusted to different contexts and environments rather than a prototype to be followed strictly.

This chapter is divided into three key sections. First, it will introduce the theoretical framework of the optimised mixed more building. The second section focuses on general design principles for the new building typology. Finally, these principles will be applied to the five case studies as retrofit and new build scenarios using a practical framework derived from the design principles.

9.2. The optimised mixed-mode building – a theoretical concept

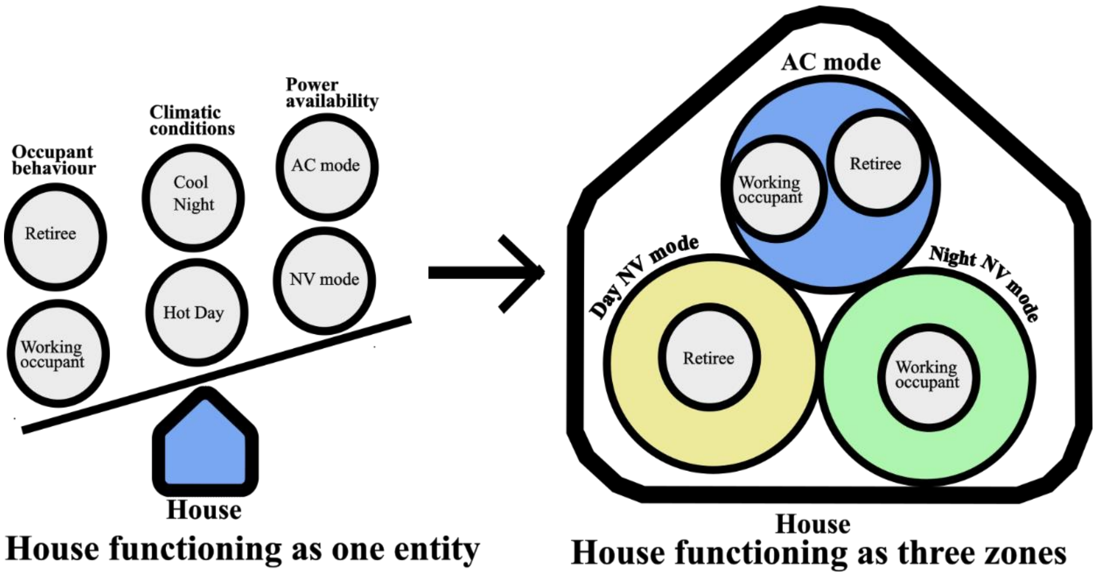

Figure 9.1 The concept of the optimised mixed-mode building. By the author

Houses in Khartoum struggle to juggle conflicting socio-climatic needs. They must be comfortable during different climatic conditions, occupant schedules, and power availability. Instead of trying to achieve all these criteria throughout the entire building, this research suggests viewing the building as a triad of zones. Each zone is environmentally optimised to run in a specific mode and time (Figure 9.1). For Khartoum, they are the AC zone, the Day Natural ventilation (NV) zone and the Night NV zone. This is inspired by the idea of thermal diversity in the traditional house but suited to a predominantly indoor lifestyle. The AC zones could be used for the peak summer periods, while NV zones could be used during power cuts throughout the year and during moderate times. The NV zones would have to be divided into day and night spaces as their design requirements differ in a hot-dry climate with a high diurnal swing. A similar concept was explored by Saini for a courtyard house (Saini, 1980).

Figure 9.2 shows Saini's proposal of a day and night use zone within a courtyard house in a hot-dry climate by varying the thermal mass thickness. Allocating a room to a specific climatic condition also has roots in traditional buildings, with summer and winter rooms in Iran as an example. Similarly, Susan Roaf proposed an example for the colder climate of the UK. She argues that when finances are limited, a person can optimise one room in the house for overheating to create a cool refuge (Roaf, 2014). The new typology to be presented in this chapter differs from these ideas in several aspects. First, it is tailored to the context of Khartoum, not only in terms of a hot arid climate but the complex cultural context of a modern African city. Secondly, it emphasises the continual use of the spaces as part of the occupant's daily life rather than to be used only in specific seasons or extreme conditions. Finally, other solutions typically focus on meeting the thermal needs of different times, while in this case, user patterns and AC use are additional parameters to be considered.

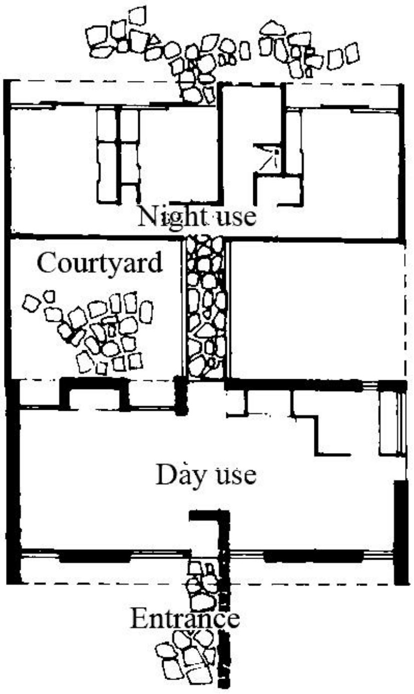

Figure 9.2 An example of varying using different construction types to create day and night zone. Source: (Saini,1980)

As mentioned in section 4.4, there is minimal capacity to enforce building regulations in Sudan. Another hurdle preventing standardisation, is the limited resources available in this context, combined with a large disparity in income. For example, these factors make it hard to specify a level of airtightness and U value that is achievable for most people. That is why the key aim of this framework is to provide architects with a flexible guide to improve building performance of houses in Sudan in an optimal way that maximises on existing resources and practices. It is about striving to achieve an incremental improvement, when the circumstances limit the ability to build high performance buildings. It relies on synchronising the space with the building fabric's performance, technology and occupant behaviour to function well, which vary considerably. This is another reason why the actual specifications of each zone will need be determined on a case-by-case basis. The examples in this chapter are used to illustrate how the framework could be applied but they are not intended to be applied as-is in projects. A future guideline will be published by the author for that purpose, a draft of it is included in appendix D.

One of the core ideas underlying this typology is using the term 'zones' rather than rooms. This is intentional as the aim is, as mentioned, not to propose a specific prototype but rather a concept that can be adjusted to suit different cases. Each zone could be one or more spaces, and it could also be an outdoor space, indoor or transitional space. A space could also be a convertible space to function as different zones. The main requirement is that it meets the thermal comfort needs while running in a specified mode and time. Choosing spaces to function as specific zones will need to be done at the architect's discretion, but section 9.3 can provide recommendations to guide the decision. This allows for flexibility to make decisions based on factors relating to the building, such as available floor area and spaces, factors relating to the occupant, such as the family structure and daily use patterns and financial factors, such as overall budget.

The zones must synchronise with the occupants' behaviour to limit the need for thermal migration, which might deter the occupants from using the building optimally due to inconvenience. This includes the occupant's space use patterns. For example, chapter 7 showed that younger occupants now use the room extensively, starting in the afternoon. However, a retired occupant would likely use the living room for most of the day and only retire to the room to sleep. Another factor is the family dynamics, the family might function as one unit and share one space, or they may have a strong male/ female divide and need two or more spaces. The family size is also a key factor; the zones must be able to accommodate all the members during the allocated time. For example, a zone could be several bedrooms or one large living room. The architect must also choose the zones with ownership and privacy in mind. Section 5.6 emphasises the importance of fostering the feeling of ownership to encourage energy-saving behaviours. The design must consider private and public ownership of spaces to ensure that the different zones are accessible to everyone. For example, one person's private bedroom cannot be the only air-conditioned space for the entire family. It is also essential that these three zones are integrated within the planned expansions. Families need the ability to live close but separate lives in a blend between an extended and nuclear family layout. Therefore these three zones need to exist in each subfamily unit or at least be accessible even if the space is subdivided. For example, a guest saloon might be shared by several families even if they have separate apartments.

Existing practices observed in this study can also be integrated into the typology. Firstly, most houses in the case study already have different construction types, but this was due to socioeconomic motives such as improved social status. The different zones could be created if this practice was integrated into a fabric-first approach. For example, the metal roof kitchen veranda is used by occupants to illegally utilise the setback space, as stated in section 6.3. From an environmental perspective, it shades the kitchen walls and provides a cool place at night due to the low thermal mass and open sides. This can be further enhanced if mosquito mesh is used and security bars for safety to encourage outdoor sleeping. The second observation was that, during power cuts, the occupants congregated in one room that had a battery in one room. This behaviour can be planned for in the design of the NV zones. For example, the space must be large enough to house the entire family and be comfortable with just a fan, which means it needs to be cooler than 32ºC (Pablo La Roche, 2020).

The optimised mixed mode building has several key strengths. Running in mixed-mode is essential from a thermal comfort perspective. Manu et al. (2016) and Karyono et al. (2015) showed that mixed-mode building occupants tolerate a wider range of temperatures than occupants of fully-airconditioned buildings. The higher expectation in AC buildings decreases the probability of occupants adopting adaptive behaviours (Vecchi et al., 2012) and hinders the acceptability of natural ventilation (Candido, 2010), both of which consequently lead to higher consumption rates. AC building occupants' reduced exposure to thermal variety also reduces their resilience as they become more likely to suffer from heat strokes when they are exposed to outdoor conditions (Pallubinsky et al., 2022). Also, in terms of resilience, increasing adaptive behaviour opportunities increases the resilience of the building itself, as it means it can function well under different scenarios. A building that is only comfortable when airconditioned would be insufferable during the 7-8 hours when the power is cut. The ability to run in both free and airconditioned mode for the Sudanese household is a necessity, not an advantage. The adaptive opportunities also provide the occupants with financial resilience as they can increase their use of them instead of the AC in times of financial difficulty. It is also a financially sustainable solution as most houses in Sudan are unlikely to afford to make the entire house energy efficient. They can alternatively focus on creating one or two highly efficient air-conditioned zones, reducing consumption compared to just adding an AC to hot rooms, which is the typical response, as mentioned in chapter 5.

9.3. General principles of design for the optimised mixed-mode building

After understanding the theoretical framework that underlines the optimised mixed mode building concept, this section will explore some general principles needed to achieve this concept. It will start by identifying the physical requirements the zones need to achieve to meet their targets. It will then look at the differences between optimising for air conditioning versus optimising for natural ventilation in a hot and dry climate. Some of the passive tools that can be used to achieve these optimisations will be further explored. These are not exhaustive examples. The architect can utilise any passive methodology, as long as it can reduce the energy consumption of zone and increases the hours of comfort within the intended time use and mode of the space.

Designing for the AC versus Natural ventilation

Passive systems utilise the available free energy from the environment to cool or heat homes. Vernacular buildings relied on these low-tech methods for centuries to regulate outdoor temperatures in the absence of active cooling, which was only invented in 1902. However, in some cases, particularly in extreme climates, they cannot achieve modern comfort levels and need active systems to support them. This does not mean using the active systems as an alternative, as the passive methods reduces the energy load of active systems. An example of successfully combining the two can be seen in Passivhaus homes, they utilise passive methods to reduce the energy consumption of heating to the minimum. They particularly focus on air tightness, high insulation rates and limiting heat loss through ventilation MVHR (Mechanical Ventilation with Heat Recovery) systems that capture heat from exhaust air. You can open a window during the summer, but the building mostly relies on mechanical ventilation. Though it relies on passive design, Passivhaus requires a high level of technical knowledge to meet the standard, and the focus on insulation and air tightness as a solution is suitable for cold climates. These characteristics are what make it ideal for the European countries it was designed for, but not necessarily for developing hot countries.

In a developed hot country context like the Middle-East, buildings are highly consumptive because they are typically fully airconditioned and natural ventilation is rarely utilised. Most Passivhaus cases for hot climates are simulations, but an experiment in Qatar showed that a Passivhaus villa reduced consumption by 50% despite only increasing costs by 20% compared to a standard villa with the same design (Khalfan, 2019). Peak consumption in the month of August was reduced from 5500 kWh to 2000kWh. Despite this success, this villa and a simulation in Dubai (Abu-Hijleh & Jaheen, 2019) both failed at meeting all of the Passivhaus standards for hot climates (Khalfan, 2019).

In developing countries, buildings are typically mixed-mode or free running, which means that natural ventilation also needs to be considered. Another key consideration is the economic viability of passivhaus because it is technology reliant, which requires sophisticated materials and labour skills.

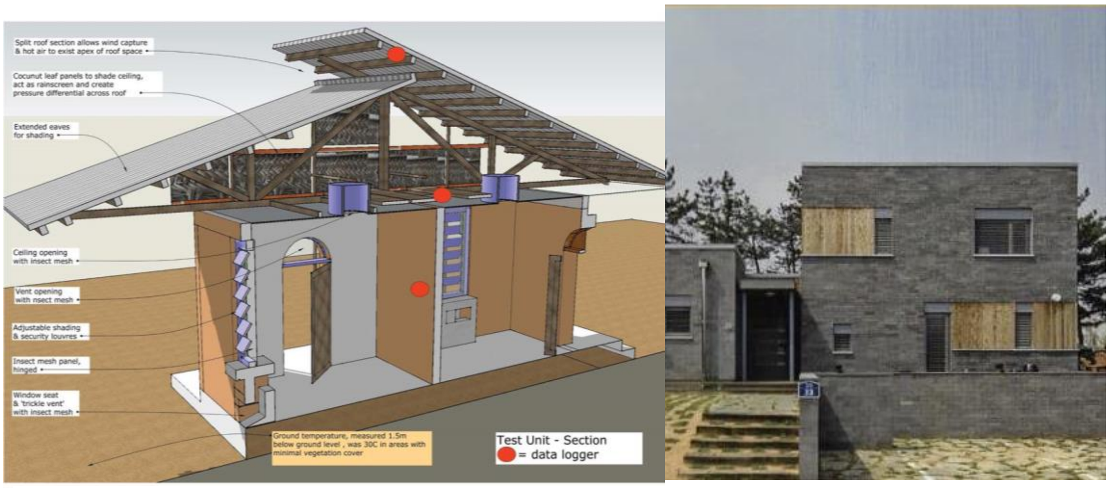

Figure 9.3 A comparison between a PassivHaus design for hot humid climates for the developing country Tanzania (left) compared to the developed country Korea (right)

Simmond Mills architects had to address these concerns in their design of an energy efficient house in the hot humid climate of Tanzania. In this instance, designing for AC use required deviating from the passive principles used for hot-humid climates. PassivHaus buildings favour the 'boxy but beautiful' concept, as shown in Figure 9.3, which is an example of a PassivHaus in hot-humid Korea (Burell, 2018). The Korean building relies mostly on the MHVR system to control the air humidity and temperature, and many components had to be imported from Germany. Simmond Mills architects ultimately chose the natural-ventilation passive design route and tried to mimic the conditions 'under a cashew nut tree' for several reasons (Simmonds, 2017). Firstly, the surrounding population spent little energy as most buildings were free running; an airconditioned building, even an efficient one, would be significantly more energy intensive. Secondly, the occupants were well-adapted to the hotter climate, meaning that the warmer temperatures achieved through passive methods were sufficient for them. Using the adaptive thermal comfort standard, the Architects proved their building was comfortable, even if it did not meet the standards required by the PassivHaus certification they attempted to achieve. The only concern is that with climate change, as temperatures increase and ACs become more widely adopted, the occupants will be forced to install ACs ad hoc, similar to our case study buildings.

The Tanzania case study helped identify the main questions that need to be addressed when trying to balance the needs of buildings designed to be air-conditioned with those designed to operate in a free-running mode. Firstly, in our case, the occupants already use the AC in an energy-intensive manner, and a sealed building will likely be less consumptive. Secondly, it highlighted the need to research the differences in designing for AC use compared to designing for passive ventilation. To answer this question, the passive systems strategies in the CLEAR guide was used as a baseline to identify the requirements for passive solutions in hot-dry climates, as shown in

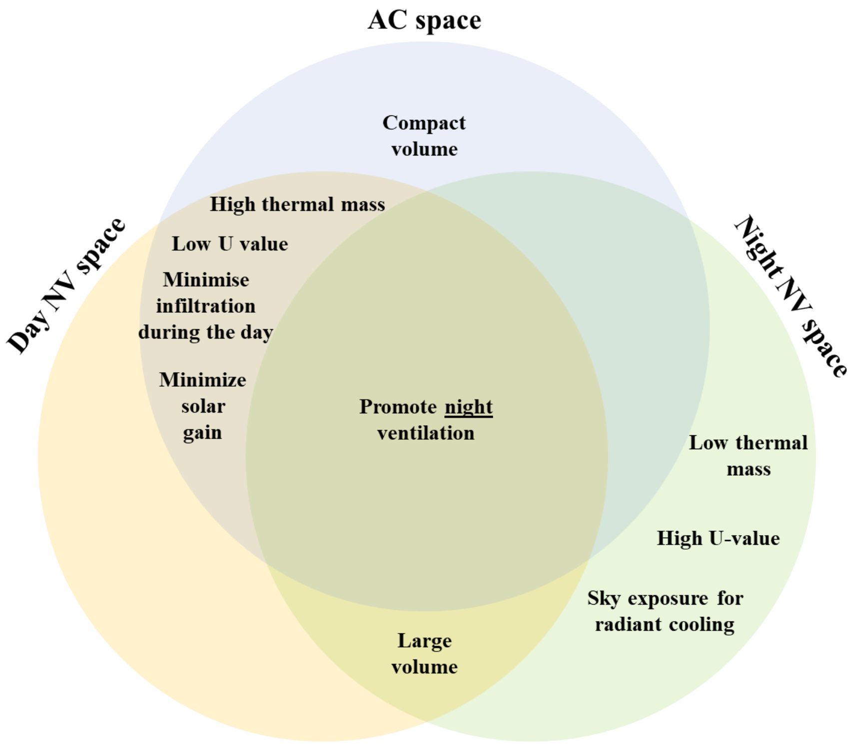

Figure 9.4 (CLEAR, 2002).

Figure 9.4 A comparison of the environmental needs of a free-running and AC building in a hot-dry climate

Figure 9.4 shows that achieving thermal comfort for AC and NV spaces in hot-dry climates is not as contradictory as in hot-humid climates. This is mainly due to the shared requirement of reduced day ventilation and increased night ventilation in all three zones, unlike the hot-humid climate, where ventilation rates differ based on the mode used.

Figure 9.4 highlights the differences between the three zones, which are needed to customise each. Even small reductions, as little as 1K, make a big difference in internal thermal comfort, especially when the thermal comfort range is small (Guimarães et al., 2013).

This section will first explore the impact of volume as it is a critical difference between NV and AC zones. The Day and AC zones seek to minimise heat flow, while the night zone prioritises increased heat flow to allow the rapid loss of accumulated heat into the night air and sky. This section will explore volume, insulation, thermal mass and shading as environmental parameters that an architect can use to customise each zone.

Volume requirement differences between NV and AC zones

The underlying concepts behind current volume choices in traditional Sudanese houses need to be reassessed in light of the current circumstances identified in this study. This would allow designers to understand the barriers when increasing or decreasing the volume of a bedroom or living room volume based on the zone it serves. Smaller spaces are more at risk of overheating due to the increased internal heat gain, which is why they are less suitable as day NV spaces (Arup, 2022). Another supporting argument for large spaces to act as the day NV space is that evaporative coolers can work more efficiently in larger spaces due to better ventilation (Ross, 2020). For each 1000 CFM of cooling capacity, an evaporative cooler needs 0.09-0.18 sqm of opening (DOE Office of Energy

Efficiency and Renewable, 2001). The larger space also means that the occupants can all share that space, where a battery can help run a fan and lights. Private spaces like bedrooms are typically smaller than public spaces such as living rooms or saloons, so the bedrooms are better suited as the AC zone, while public spaces can become the day or night NV zones.

The 4x4m standard room size in Sudan came as a structural constraint, as this was the most extensive roof size that could be affordably constructed using traditional building techniques (Sandison, 1953) However, that was set before the 1950s, and construction materials and people's spatial needs have changed. Section 2.6 discussed increased individualisation, reduced social ties, reduced birth rates and increasing nuclear families as part of the trend towards modernity. This is reflected in how the contemporary house designated rooms for the nuclear family's children rather than having a shared room for females or males, as discussed in section 2.6. This change shows that the function of the 'room' has transformed from a communal multipurpose space (Merghani & Hall, 2001) to a private space inhabited by specific individuals. Thus, the room's size should reflect the expected number of occupants, leading to a smaller room if it is just for two occupants, which is the officially accepted norm (Hamid, 1986). All five case studies had 1-2 occupants per room. However, Khartoum's official number of persons per room has risen from 2.7 in the 1970s to 2.98 in 2014 (Central bureau of

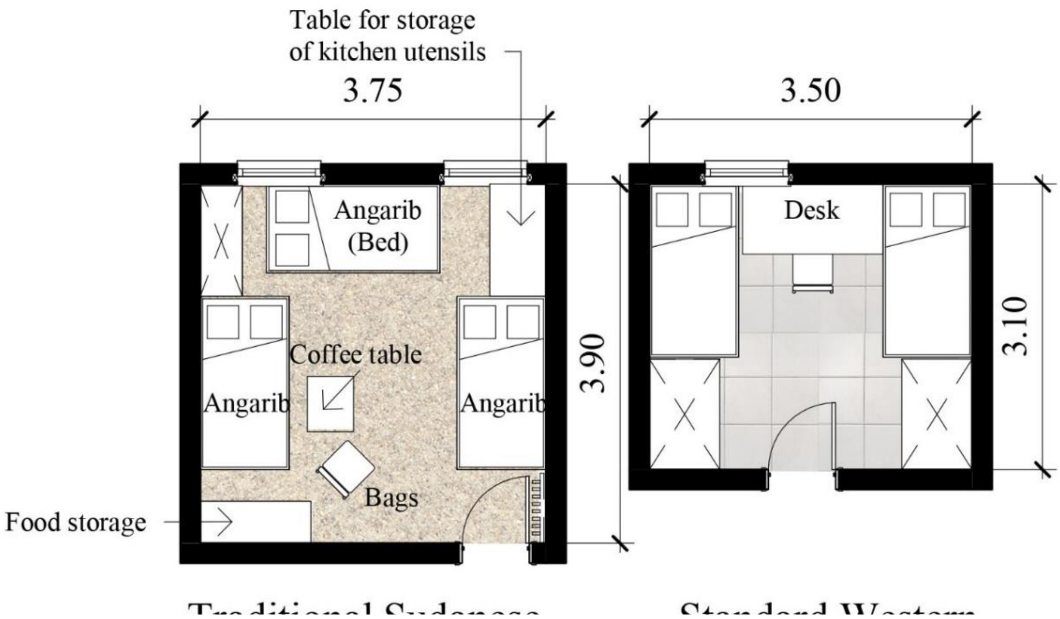

Figure 9.5 Left: A sketch showing the typical furniture layout for a room in Khartoum with the main function of storage and receiving guests. Source: (Elias, 1970b). Right: a modern double bedroom from Neufuert standards 4th edition

Statistics, 2014) because the survey included the crowded lower-class areas mentioned in chapter 4. The family size in a third-class area is 8.9 compared to 5.8 in first-class areas (Statistics, 1993).

The furniture layout must also reflect the use change, which impacts the room size. The room was typically used as storage mainly or for receiving guests, which is why it only had beds and a cupboard (Elias, 1970b). However, chapter 7 shows that rooms are used extensively, not just for a few hours at midday, which necessitates furniture such as a desk for homework or a laptop. Figure 9.5 compares the typical room furniture and the proposed furniture in Neufert's standard, with a clear area of 10.85 m^2 compared to 14.62 m^2 of the typical room.

A smaller room might have reduced natural daylight from the smaller window area. Therefore, the architect needs to use daylight simulation to ensure the smaller room has sufficient daylight. This prevents overreliance on artificial lighting, which increases internal heat gains. Another important consideration is the occupants willingness to accept a smaller space, particularly in wealthier households where large spaces are linked to increased status. The architect would need to use thermal simulations to show the potential energy savings from the smaller space. A sample real room would also be needed to enable the occupants to visualise what the smaller space would feel like to ensure they make an informed decision. During the interview with civil servant 1, he mentioned that people are already illegally building smaller apartments that don't meet current spatial regulations. He further elaborated that the government has acknowledged the increased demand and is currently amending building regulations to allow for small apartments and even studios, which did not exist in Sudan prior to 2010. This demand must be met in a way that is conscious of the functional, environmental, and social impact of smaller spaces, as elaborated on in this section.

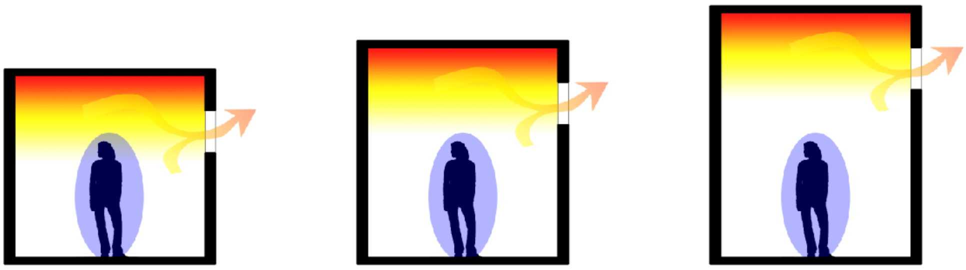

Figure 9.6 The impact of roof height on thermal comfort due to air stratification stratification. Source: (Guimarães et al., 2013)

Regarding roof height, a higher ceiling keeps the hot air away from the occupants (Figure 9.6), but there is conflicting evidence to the optimal height. The traditional view has been that increasing the ceiling height over 2.7m (Ahmed, 1978) and 3m (Mclean & Hunt, 1911) is unnecessary. A more recent study in Brazil found that from 2.6m, every 20cm height increase led to a temperature reduction of one degree (Guimarães et al., 2013). An important consideration is the height for ceiling fans; the ceiling must be at least 2.4m to provide the necessary 7 ft from the blade to the floor. High roofs help with stack ventilation, which is why traditionally, saloons had high windows and floor-to-ceiling heights of 4 meters. However, these windows are rarely opened due to accessibility issues, which defy their purpose. Mclean used vents with mesh wiring for mosquito and dust control (Mclean, 1910). If the room size reduction shown in Figure 9.5 is combined with a reduction of the ceiling height from 3m to 2.6m, the overall volume will reduce from 43.65 m^3 to 28.21 m^3. This means a smaller air volume for the AC to cool which requires less energy.

High and low thermal mass in Day versus Night spaces

As mentioned in section 2.2, the hot night temperatures in Sudan make high thermal mass buildings very hot at night; sometimes, they cannot cool before the following day. This is not an issue for Day NV spaces as the space is not used at night. In the AC zone, the rooms need to be precooled using night flushing before turning the AC on at night. Otherwise, the AC will expend a large amount of energy to dissipate the heat accumulated during the day. Thermal mass is beneficial in AC spaces even if they are used intermittently, unlike cold climates with active heating, where intermittent use makes the thermal mass increase energy expenditure (Reilly & Kinnane, 2017). For the night NV zone, the time it takes to cool the thermal mass creates discomfort in the evenings. Therefore, the structure needs to be lightweight.

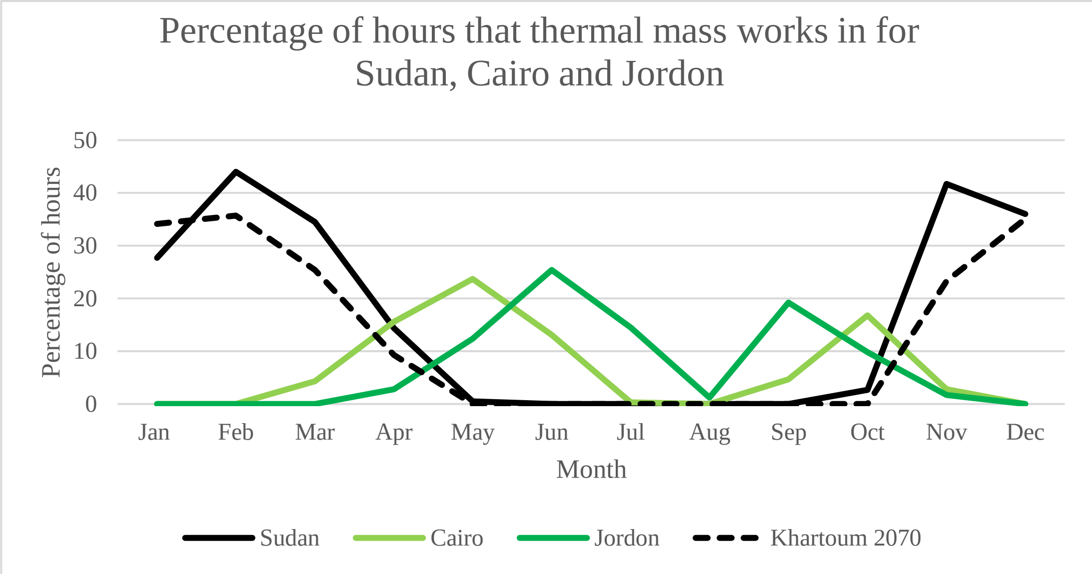

Figure 9.7 Thermal mass performance annually in Khartoum, Jordon and Cairo

Figure 9.7 shows thermal mass performance throughout the year by showing the percentage of hours thermal mass works well for in Khartoum, Khartoum in 2070, Cairo and Jordon, using Climate Consultant. The ASHRAE standard 55 was used to calibrate our results with Abdelsalam's (2019) research. Figure 9.7 shows that, in Khartoum, thermal mass works best in the dry winter season between November and March. As temperatures increase in 2070, thermal mass performance is expected to decrease further. This is important for designing zones as it indicates that the thermal mass alone cannot keep the building cool from May to October. This means that the Day NV zones need evaporative coolers, or they will be uninhabitable during the summer, as is the case for the hot room M1-SE.BD, as discussed in section 8.4. In Cairo and Jordon, the cooler temperatures mean that thermal mass worked best in the summer, when it was hot during the day and cool at night.

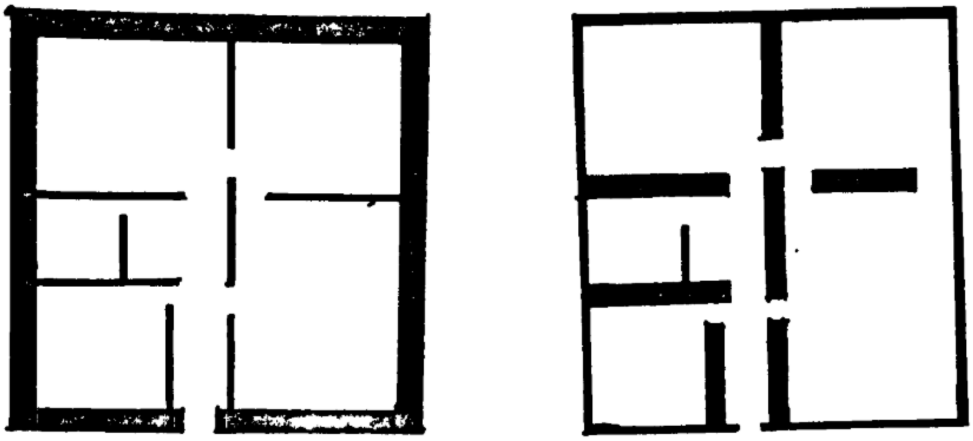

Figure 9.8 Recommendations for locating thermal mass in hot dry climates source: Ahmed (1978)

Locating thermal mass needs to be strategic, especially because of the differing requirements of the night and day zones, which will likely be adjacent for convenience, such as in an apartment. Saini's idea of separating the two zones with a courtyard (Saini,1980) is space-consuming. Unlike thermal mass in cold climates, which needs to be located in areas of high sun exposure, thermal mass in hot climates is recommended in internal spaces rather than externally to shade it from the sun. At the same time, the external parameter can be insulated (Figure 9.8). This, however, means that it is even more critical to utilise night ventilation as the thermal mass would now also be away from the windows.

Combining High and Low U-values with variable ventilation rates in day and night spaces

During the day, the main aim for the AC zone and day NV zone is to minimise conductive heat transfer. This is done through insulation which lowers the building fabrics' U-value. The placement of the insulation also needs to be strategic. A study in Mexico found that it is best to keep the insulation to the roof, walls and window while allowing the ground to act as a heat sink (Lucero-álvarez et al., 2016). Khartoum is built on agricultural land that has black cotton soil that expands and contracts significantly with rainfall, causing damage to directly connected floors. Therefore, caution should be taken when using the ground as a heat sink by protecting the floor with a concrete slab. In instances where there is a high internal heat load, such as from office equipment or cooking in the kitchen, insulation can be detrimental as it would trap the heat inside. This would require the AC to expend more energy to lower the temperatures as it has to counter two loops (Section 8.3): the heat produced inside and the heat coming in from outside.

The Mexican study emphasised that although the aim is to keep the heat out during the day, the structure must also be light enough to dissipate that heat during the night (Lucero-álvarez et al., 2016). This means that, due to the diurnal swing in hot-dry climates, the insulation would also reduce the reverse heat transfer from the hot building interior into the cool night, especially if combined with high thermal mass. Therefore, it is crucial to ensure adequate night ventilation for the day NV zone and the AC zone.

This must consider occupants' behaviour; as discussed in section 6.5, due to safety concerns, only one male occupant still opened the windows at night. The architect can educate the occupants about the importance and impact of night ventilation and ensure they address any concerns regarding security and mosquitos. An alternative would be to install a whole house fan that runs automatically, as the extensive cooling season would mean the fan is used for most of the year, which makes it more feasible.

As mentioned previously, a low U-value for the night NV space would limit the space's ability to cool rapidly at night as it would deter the reverse heat flow at night. A sheltered outdoor space like a rooftop cover with mosquito nets or the kitchen veranda would work well as a night NV zone. It provides shade for the roof and kitchen and is a cool refuge during night power cuts. Another suggestion would be a lightweight bedroom designed for night use only, for example, if it is occupied by males who spend most of their time outside the house.

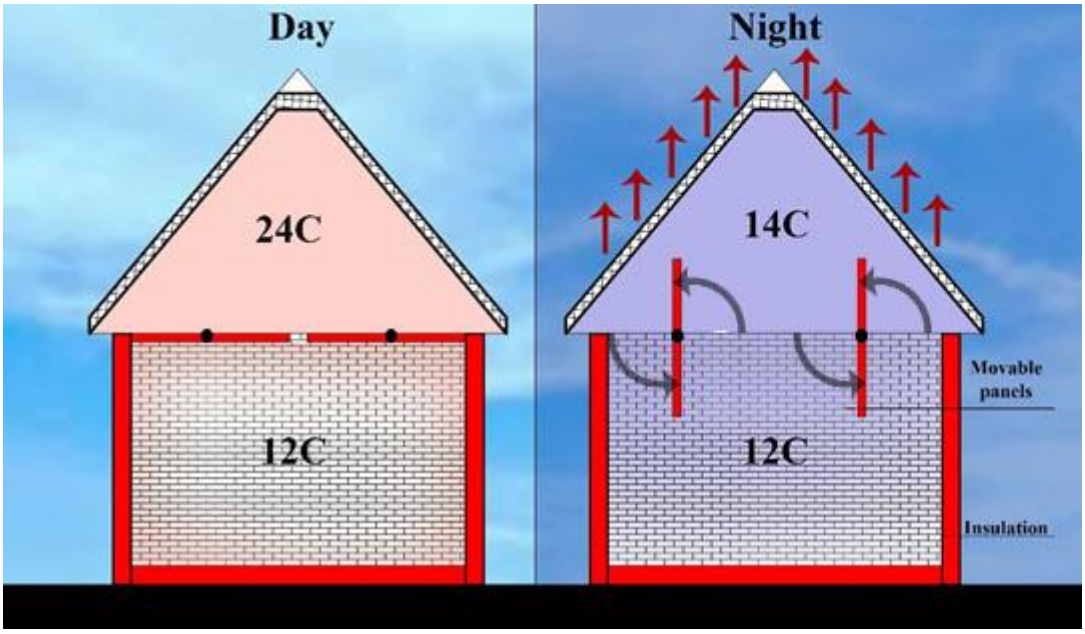

Figure 9.9 Convertible spaces with movable panels. Redrawn by the author. Source: (Pablo La Roche, 2020)

Insulation in the roof especially would also hinder a space's ability to radiate heat at night. To counter this, a study proposed using movable roof panels that twist at night, exposing the internal insulated surfaces to the roof (Figure 9.9). The conversion would allow the space to be insulated during the day and rapidly cooled at night, effectively working as both day and night NV spaces.

Insulation thickness needs to be optimised to avoid Anti-insulation. Anti-insulation is where increasing the insulation thickness and cooling set point leads to more energy consumption for cooling (Idris & Mae, 2017). Anti-insulation is less problematic in hot-dry climates than in hot-humid climates (Idris & Mae, 2017). It is a more significant issue in spaces with high internal gains. The increased insulation can also hinder the night cooling of thermal mass. Insulation is expensive in Sudan, in 2020, it cost 110-200 dollars per cubic meter, while energy costs only 0.089 dollars per kWh (Khalid et al., 2020). All these factors make it vital that insulation is used strategically, and in areas of high priority. Thermal simulation in a case-by-case basis is needed to determine the best thickness for each case based on available budget.

Another factor to consider when designing for the AC is the wall layer configuration. When the AC is used intermittently, the insulation in the wall cavity consumes 72% less energy than a wall insulated on the outside and inside (Idris & Mae, 2017). However, if the AC is used consistently, the layer configuration does not have a significant impact. This information is key to this study because the occupancy schedule dictates the layer's configuration. This means that for our hybrid solution, choosing the layer configuration depends on the definition of the AC zone. The best configuration for residential spaces is to locate the thermal mass internally and the insulation externally (Idris & Mae, 2017). The set point must not be more than 30ºC to avoid anti-insulation behaviour (Idris & Mae, 2017).

Minimising solar gain in day spaces

Minimising solar gain is crucial for the day NV zone to prolong comfort during power cuts and for the AC zone to reduce the energy consumption of the AC. The Day NV zone is the most sensitive as it has to handle a high cooling load with limited access to mechanical ventilation. Therefore, when choosing the orientation for the zones, the most shaded areas should be the priority for the day NV zone. This could be the northeast or north-central orientation, near a high-rise neighbour, or under partial roof shade due to a roof veranda or upper floor. In apartment buildings, living rooms are often sheltered by peripheral bedrooms, which is why they make ideal day NV spaces, provided night ventilation is provided. On the other hand, night spaces and storage can be used as buffer zones to shade the AC and day NV zones from high solar radiation zones such as the southwest orientation.

Another key factor in limiting solar radiation is windows, by optimising their size and shading them. The preferred window-to-wall ratio (WWR) in hot-dry climates is smaller than in hot-humid climates (Alwetaishi, 2019), where ventilation is beneficial to reduce humidity build-up.

Figure 9.10 Windows and doors in converted verandas in the traditional houses T1 and T2

The WWR in our case study buildings in three sampled rooms was between 20-35%, with converted verandas having the largest windows, as shown in Figure 9.10. This large WWR poses a risk that architects must address when retrofitting traditional buildings if the spaces are to be used as Day NV zones or AC zones.

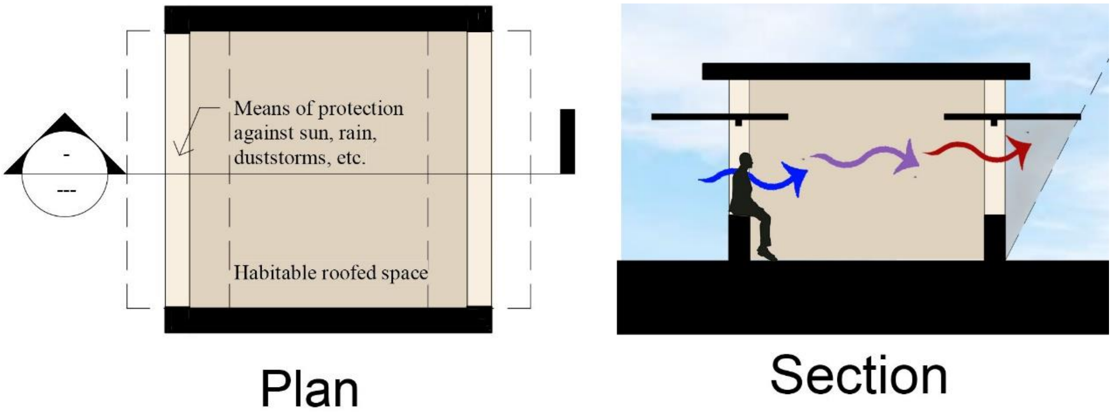

Figure 9.11 A convertible indoor/outdoor space that can increase ventilation rates at night allowing for better night comfort. Source: (Elias, 1970)

However, if they are used as night NV zones, they present an opportunity to be converted using the idea proposed by Elias in Figure 9.11. (Elias, 1970b) He proposed using large openings that can allow for higher ventilation rates when needed. It also allows for the convenience of converting an internal space into an outdoor one with minimal effort, as no moving furniture is involved. This also means that the occupants are less likely to expand into that space as it already functions as an indoor space.

9.4.Demonstrating the practical application of the framework

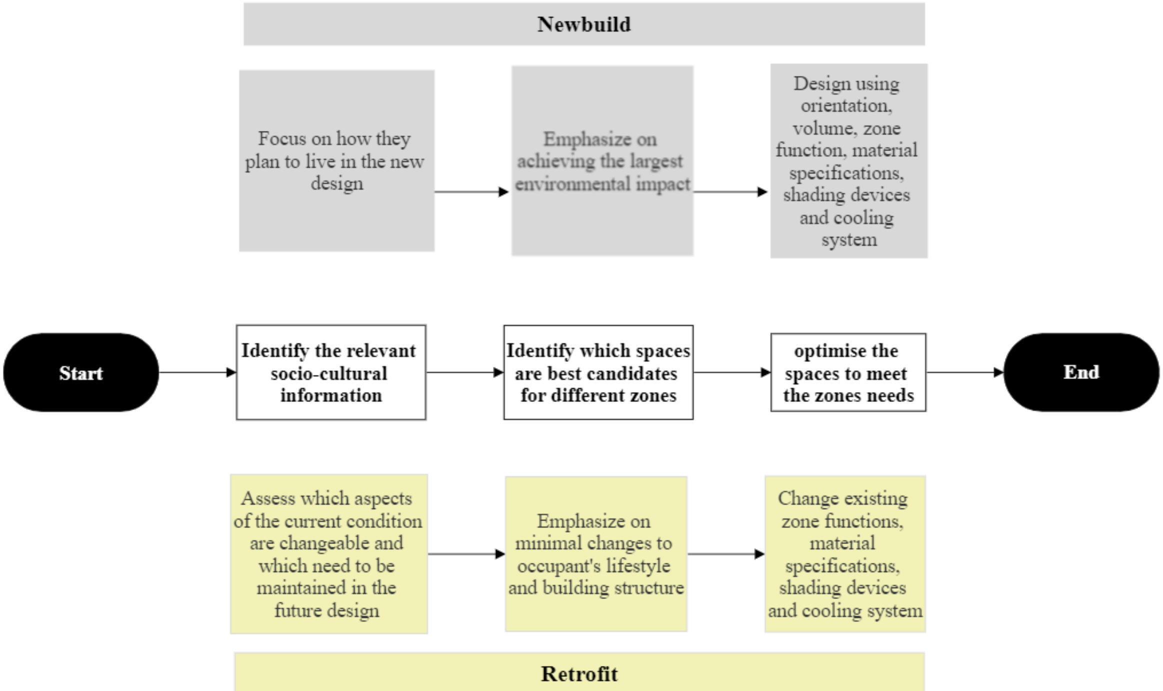

Figure 9.12 A flowchart showing the steps needed to create an optimised mixed-mode building in both new buildings and retrofits

The theoretical framework explained in the previous sections has to be tailored case-by-case; this research proposes a methodological framework that can be used to design or retrofit buildings according to the new typology, as illustrated in Figure 9.12. The first step is to identify the relevant sociocultural information about the occupants and how they currently use the building they occupy. Then this information needs to be processed to extract how it may impact the design of the zones. For a new build, this includes how they live and how they expect to change in the new design. For example, they might be adding more bedrooms in the new design, which reduces the number of occupants per room and allows you to reduce the room size. Another example would be if an adult child is planning on getting married soon, and provisions need to be made to create zones for two nuclear families rather than one. For retrofits, it is vital to identify which aspects of the current conditions are changeable to allow you as much freedom to make changes. For example, suppose a frequently used living room/ day zone is located in a hot location. In that case, it might be better to switch another space function into a living room, which would cause less disruption to the house than upgrading the living room building fabric. This solution would only be accepted if the data collection showed that the changes do not impact any crucial needs like the segregation of sexes.

The second is to identify which spaces are the best candidates for the three zones, depending on the information gathered from step one. In a new build, the key criterion is achieving the most considerable environmental impact, while in a retrofit, minimising the disruption to the occupant lifestyle and the building is critical. For example, the initial research may have revealed that the current number of spaces is insufficient to meet all the zones' needs. In a new build, a new space can be easily added and located in an optimal position within the design. In a retrofit, the designer might have to resort to convertible spaces to combine the function of two or more zones in one space.

Finally, the spaces need to be optimised to meet the zone requirements. If the design is a new build, the architect can alter a broader range of the space's parameters, such as changing volumes, orientation, space functions, material specifications, shading devices and cooling system. If the design is a retrofit, the possible changes are more limited, especially with a tight budget. Therefore, step two becomes increasingly essential.

To illustrate how the framework can be implemented, two examples will be demonstrated. The traditional house T2 will be used as a retrofit example, while M2 will be reimagined as a newbuild since most newbuilds are likely to be modern houses. T2 and M2 are the most representative samples of our five case studies. This is because the plan in M2 is more common as a hybrid villa than M1, which has two floors functioning as a villa and an additional apartment floor. This is likely because M2 was designed in the late 1990s compared to the late 1970s in M1. T2 was chosen as the institutional house design is widespread, whereas T1 and T3 have extensions guided by their specific site restrictions and family changes, making it harder to generalise findings.

Reimagining the modern building M2 as a newbuild

The first step is identifying the relevant social information and examining its expected impact on the design. The occupants in M2 are a nuclear family that lives an individualised modern lifestyle. This means that bedrooms are expected to be assigned to specific individuals, and due to the family size, each room should have just one or two occupants. This means the room size can be reduced if needed for an AC zone. The retired parents spend their day in the living room, kitchen and yard, while the entire family has dinner in the living room at 5 pm and leaves around 7 pm to retire to their bedrooms. This means that the living room needs to remain comfortable not only during the mornings and afternoons but also in the evenings. The children spend most of their time after school or work in their rooms; therefore, their bedrooms are expected to be used from the afternoon till the following day. The building upstairs has apartments that are primarily for the children's expansion in the future but could also be rented. This puts a constraint on sharing zones as the renters are not related to the family members. It also means that they can temporarily share zones when the family expands into a household phase. However, some level of male/female segregation may be needed if each nuclear family's needs are not met within their designated spaces.

The next task is to choose the zones. In this case, this is relatively straightforward. The large volume and predominantly day use of the living room makes it the best candidate for the day NV space. The compact bedroom size and extensive use from the afternoon till the following day means they are best as an AC zone. Two-night zones need to be created for this case, one for the nuclear family and one for the renters and future nuclear families. The nuclear family can share a veranda on the ground floor, while the renters can use a roof veranda.

The third step is optimising the zones based on the requirements of each zone. The day NV zone is typically the most vulnerable; this is exacerbated in this case as it is used in the evenings, not just the afternoons. This means that if a thick thermal mass wall with insulation is used, it might be too warm by the evening due to the thermal lag. This necessitates including an evaporative cooler to extend the evening comfort period. The living room can be placed on the Central North side to reduce solar gain, with spaces buffering the east and west orientations. It is preferred that it has both southern and northern windows to allow cross ventilation and faster cooling in the evenings, as shown in Figure 9.13. The staircase in the northern wall can be used for stack ventilation by installing a whole house fan in the stairwell.

The bedrooms' size was reduced from $14.4m^2$ to 11.5m2, and the height was reduced to 2.6m by installing a vented false ceiling, shown in Figure 9.15. This reduces the volume of the rooms to $30m^3$ instead of the current $43.32m^3$. Using a false ceiling strategically avoids reducing the room height in larger spaces such as the Saloon and living room.

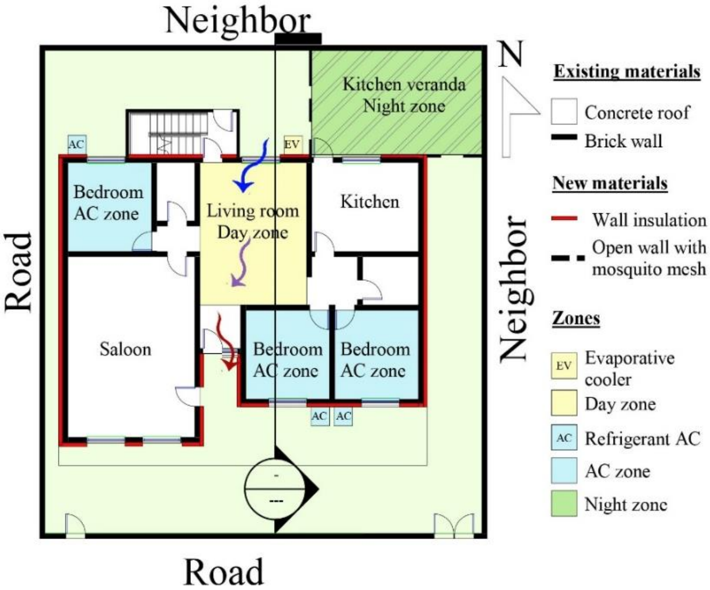

Figure 9.13 A plan of M2 reimagined from a climatic lens

The night zone could be divided into two zones, a kitchen veranda for the main family and a roof patio with mosquito mesh for the renters. The roof patio was positioned above the living room to shade it, which was also ideal as it was adjacent to the stairwell for direct access. As the occupants plan to increase floors gradually, the roof patio needs to be dismantlable so that it can be moved to the new roof with each addition. Though ideally, the kitchen and veranda would have been placed in the southeast to shade the southern walls, exposing the veranda to the southern public yard would reduce privacy. This is an example of balancing environmental needs with sociocultural considerations. The Kitchen veranda was covered in metal rail grid as shown in Figure 9.14 to ensure security. Both verandas are to be fitted with mosquito nets and battery-powered fans if the wind speeds are minimal.

Figure 9.14 An example of a lattice metal bar secured patio

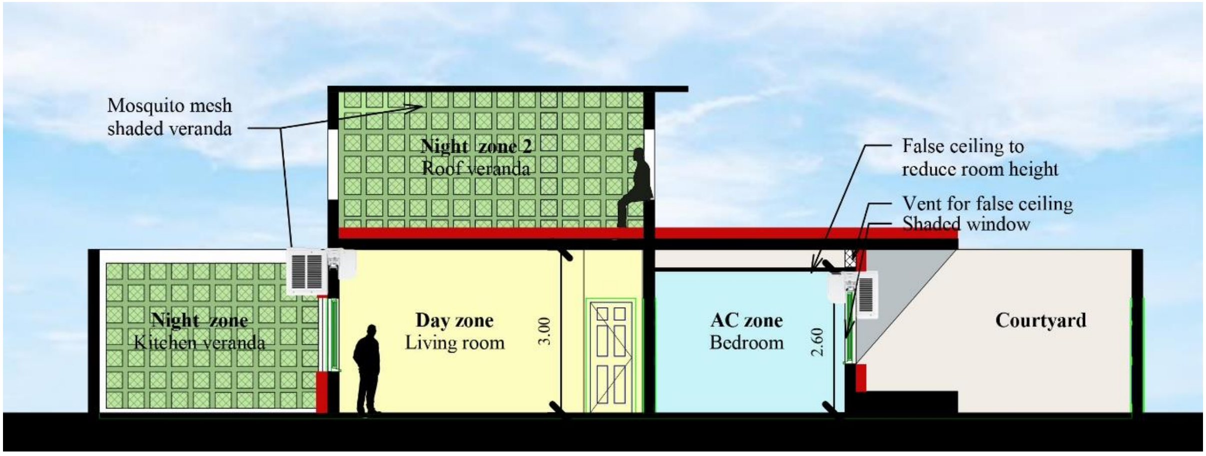

Figure 9.15 A section showing M2 with the day, night and AC zones

The Saloon is an infrequently used space; therefore, it was placed as a buffer in the hottest corner of the house, the southwest. The bedroom beside it was kept in the same location as it serves as the boy's room allowing them access to the Saloon and a private W.C. as part of a 'male zone'. The southern walls were shaded with an extension of the above floor, which expanded the space for the upper floors to be divided into two apartments per floor. As this is a new build, exterior insulation (shown in red in Figure 9.13) will cover the walls and roof to protect the day NV and AC zones. The exact thickness would need to be determined by thermal simulation. The design was kept simple and compact in line with PassivHaus's form factor recommendations.

The retrofit of T2

Retrofits require more planning to achieve optimal results with minimal disruption to the house. The Case of T2 represents a typical household family at the end of its lifecycle. Most of the original nuclear family members have their own dwelling elsewhere; the remaining members represent one to three remaining from each nuclear family. They live a communal lifestyle with a strong male/female divide. This means that they cannot share one zone. It also means that rooms are not allocated officially to specific people, which allows for more flexibility in assigning zones. The Males use the Saloon NE.BD (Figure 9.16) for siestas with the evaporative cooler on and open the windows at night.

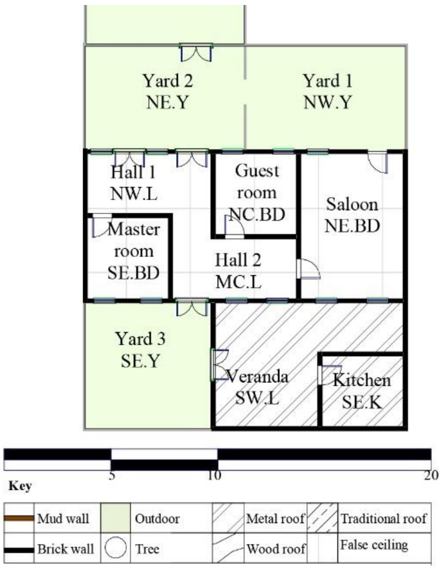

Figure 9.16 A plan of T2 in its current state

Therefore, the Saloon has to serve a dual day/night function. The females spend their day outside the home and return in the evening to spend time in SW.BD before retiring to sleep in different places. This means that the communal space that needs to be large is the night space in this instance. However, someone is always home to guard the house during the day. This means that the day NV space does not need to be large. Though the occupants in T2 intend to demolish the building in the future and rebuild it as a multi-story building, their current thermal condition is highly uncomfortable. Therefore, changes need to be as cost-effective as possible. The two bedrooms are occupied by one sister who uses the AC excessively and the other, who dislikes it and rarely uses it. This means that just one bedroom needs to be an AC zone in this case, rather than both, especially given that all the females have access to the room.

The Saloon has to function as all three zones. The AC zone is one of the bedrooms, though it is currently the northern room NC.BD, it needs to be switched to SW.BD, as this room has a higher cooling load and would benefit from an AC. Figure 9.17 shows how the southern room SW.BD is hotter than the northern room NC.BD.

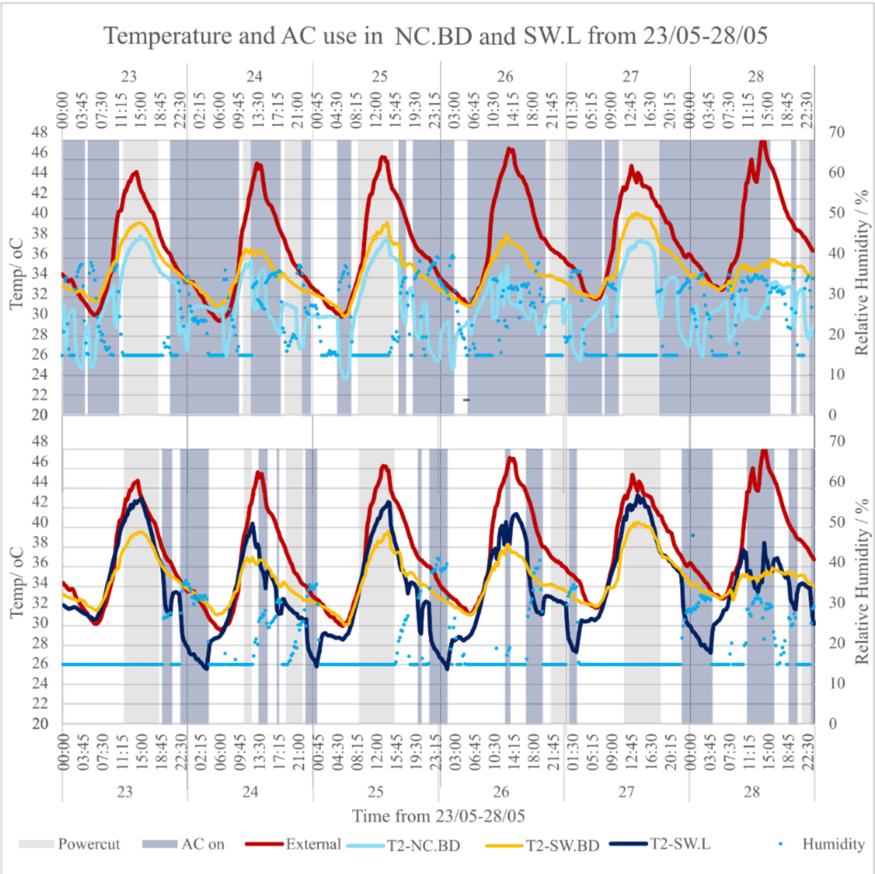

Figure 9.17 A graph showing the temperatures and AC use in T2-NC.BD and T2-NW.BD from 23/05-28/05

The Day NV space can be the hall MC.L as it is sheltered with the southern wall shaded by the veranda SW.L. The night space can be the veranda SW.L as it is already used in that capacity. These changes mean that the occupants do not need to change their daily habits to adjust to the zones, which is vital to ensure that they commit to using the zones as intended.

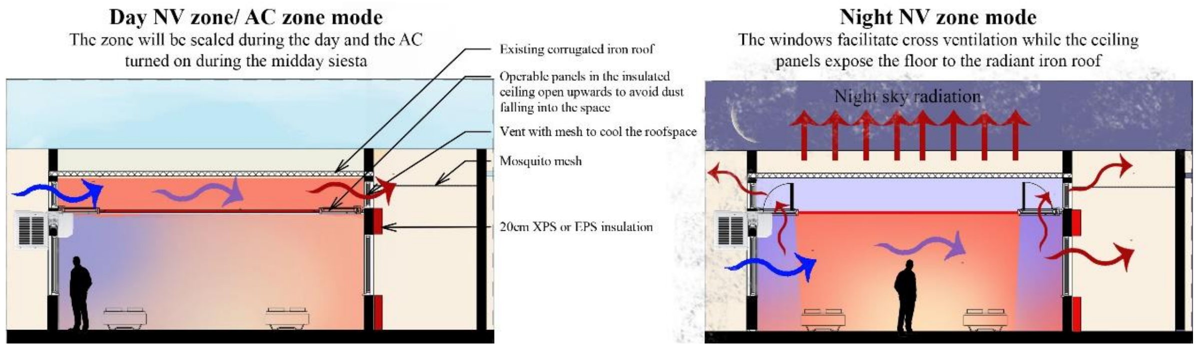

Figure 9.18 Two sections showing the convertible saloon NE.BD function as a Day NV/ AC zone (Left) and night zone (right) by author

The third step is optimising the zones. For the Saloon, a convertible space is necessary to satisfy the current use pattern. The false ceiling could be replaced with insulated panels. The panels near the southern and northern walls could be openable by rotation at night to allow thermal mass exposure to the metal roof, in addition to opening the window. Figure 9.18 highlights the openable panels at night. The veranda SW.L's iron roof extension to the east wall blocks the ventilation for the southern saloon windows; therefore, it should be replaced with a mosquito mesh to allow ventilation without mosquitos.

Figure 9.17 shows that in its current state, the veranda SW.L is usually 32ºC or more in the evening from 5 pm. This is despite being a lightweight space. It is likely due to its low exposed roof, which keeps the hot air near the occupant level (Figure 9.18); it needs to be raised with north and south upper vents to allow cross ventilation (Figure 9.19). Another issue is the metal walls shown in Figure 8.18. The space would have performed better with less metal to heat up and radiate heat.

They should be removed and replaced with a grill similar to Figure 9.14. Entering from the hall MC.L to the veranda requires going outdoors, which makes it a safety risk at night. Therefore, the grill wall should be moved to the west to include the door in MC.L within the safe veranda area. Though ideally, insulation should be used for the entire roof and exterior walls (excluding the veranda), this would be cost-prohibitive in this case. The priority is to insulate the roofs of the AC zone SW.BD and the Day NV zone MC.L and the entire southern wall if possible. Figure 9.20 shows these upgrades and where each zone will be.

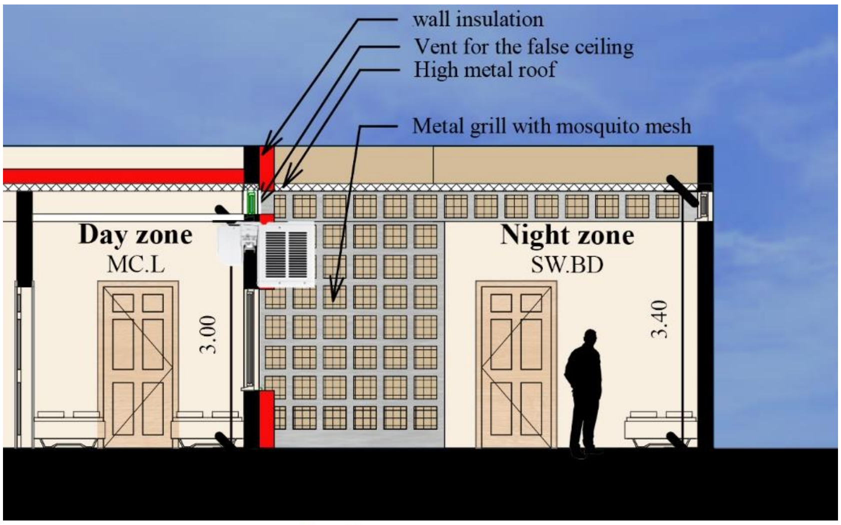

Figure 9.19 A section showing the day and night zone in the upgraded version of T2

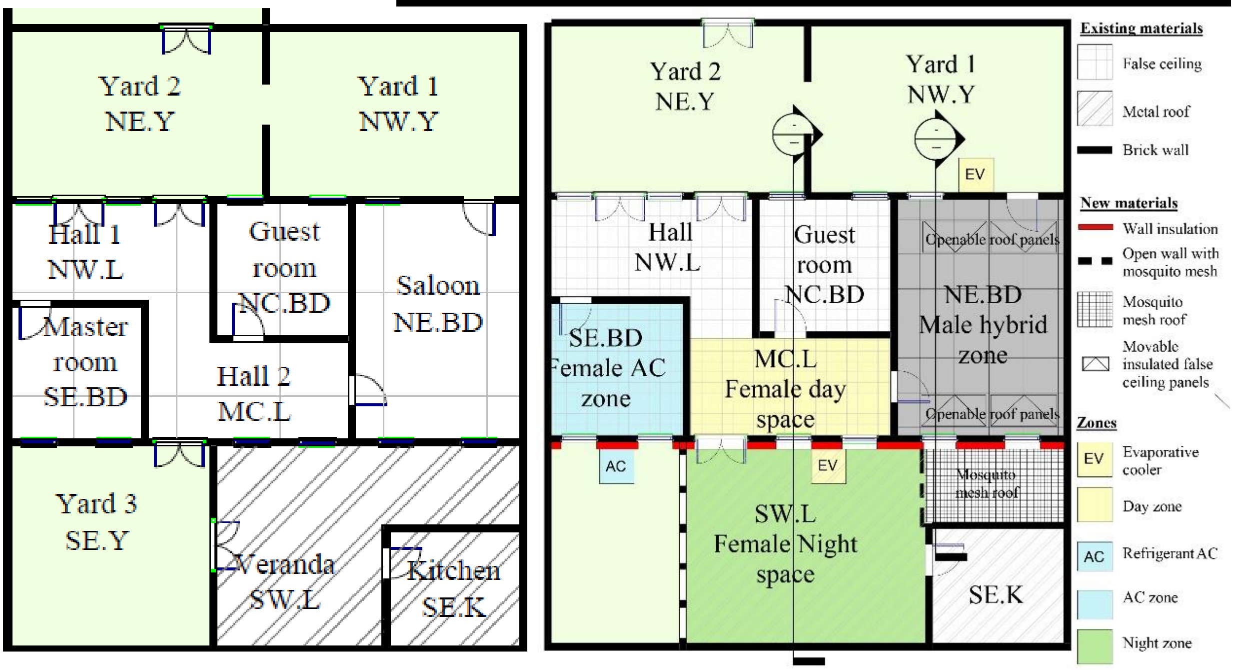

Figure 9.20 Upgraded T2 plan compared to the original setting

Adapting the typology for other contexts

The typology and framework can be used in other contexts in the global south, both hot-dry and hot-humid. The difference would be in the type of sociocultural parameters and how to achieve the needed zones. The number of zones could increase or decrease depending on the diurnal swing and use patterns. For example, in a hot-humid climate, the day and night conditions are similar, which means you only need an AC zone and an NV zone to reflect extreme and mild conditions. The key difference between the two zones is ventilation rate and volume; they both need minimal thermal mass and high insulation. The living room would still be the best option for the NV zone, while the bedrooms are the best for the AC zone. However, as the temperature is mild most of the year, with the exception of peak summer days, the 'AC zone' is preferably designed as a convertible zone. For most of the year, it could function as an NV space; however, there needs to be an option to seal these openings and use the AC when needed. This was suggested to the architect to optimise the design discussed in section 0 for climate change. Provision for installing glass panes to seal the bedrooms if needed will be added along with additional insulation to the entire building.

The concept can also be easily adapted to the scope of buildings other than residential buildings. It would depend on the occupant use pattern, the climatic needs throughout the day and the available variation that can be accentuated to meet different needs. In the context of office buildings in Khartoum, there is no night use, eliminating the need for a night zone. However, power cuts also impact offices, necessitating a day NV space. Instead of a living room, this could be a well-shaded high-thermal mass meeting room connected to a battery to power the fan, lights and sockets for laptops. If powered by a solar panel, this would ensure enough energy until the power comes back. Artificial lights allow the space to be in the centre of the building, with a smaller cooling load. However, it would need adequate night ventilation, or it would not cool efficiently for use the next day. The offices can be compact, instead of an open plan which would be difficult to air condition. The concept of buffering the key zones with unused spaces also applies to store rooms, kitchens and outdoor porches.

For more developed hot-dry and hot-humid climates, the framework's success depends on the occupant's willingness to adopt adaptive behaviours, which may be more challenging if they are used to fully conditioned buildings. This can be measured through interviews, surveys and pilot projects. Otherwise, the concept can be loosely adopted to address other conflicting needs that would be cost-prohibitive to provide for the entire building, such as daylight, air quality or ventilation rates, acoustics or humidity control. The zones would then reflect these needs. For example, if a house is near a noisy train line or road and it is not possible to sound insulate the entire house, the zones would be quiet zone and noisy zone. If the trains stop at night, the priority would be to insulate the spaces used during the day, such as the living room.

9.5. Conclusion

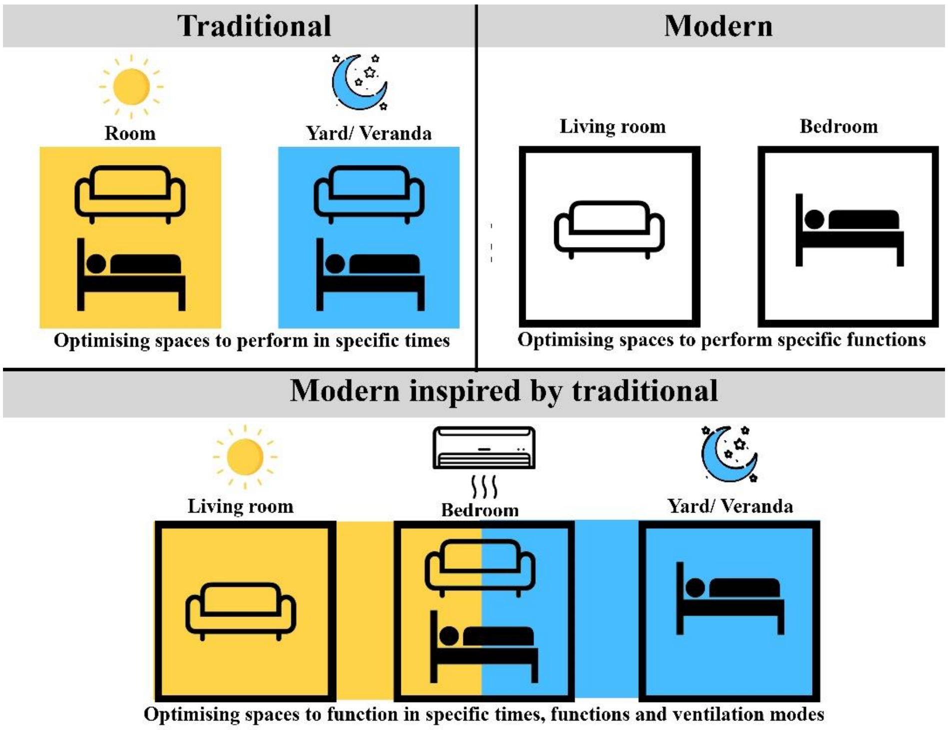

Figure 9.21 Specialising spaces based on a traditional, modern and modern inspired by traditional views

Section 6.1 mentioned how Africans seek in modern buildings the conceptual cultural needs that traditional buildings fulfilled, not their aesthetic. This is what this typology seeks to address. It combines the traditional view of specialising spaces based on their environmental performance, like multipurpose rooms for midday use and courtyards, with the modern view of specialising spaces based on function, such as bedrooms and living rooms. This is illustrated in Figure 9.21. The typology is also embedded in current practices and user behaviours, making it a natural extension of both the past and present.

A noteworthy aspect of this typology is that it considers materials not in the sense of modern and traditional as they are associated with, but rather the material's thermal properties. This pragmatic view gives the concept of optimised mixed-mode buildings the flexibility to be applied to both traditional and modern buildings. This has implications from architectural conservation perspective, because it means that for existing buildings, you can use heavy masonry where it exists or light roofs, preserving the building's identity while repurposing the building to suit a modern lifestyle.

This research is an attempt to integrate the AC holistically into local environments instead of eliminating it. If the AC is imagined as an invasive plant species, this research advocates for solutions that 'naturalise' it, to integrate it holistically into local ecosystem instead of attempting to eradicate it. It advocates for a shift from cookie-cutter solutions to bespoke ones that not only tackle the local underlying causes of AC reliance but also meet the occupants' sociocultural needs.

This solution heavily depends on the occupant, which is why it is crucial that occupants are aware how they can utilise the building in an efficient way. The issue of AC habituation in occupants also needs to be addressed to avoid the rebound effect. It is possible the improved building fabric could lead to occupants setting a lower set point, negating any savings from the improved AC zone. This could be through behavioural campaigns emphasising the importance of adaptive behaviours and maintaining a higher set point to reduce energy consumption.

Chapter 10 Conclusions

This final chapter reflects on the research's key findings, the methodologies used, and their significance. It then discloses the study's limitations and speculates how future research can progress the work.

This research aimed to create a design framework for sustainable houses in Sudan that allows users to maintain a modern lifestyle with a smaller energy footprint. The optimised mixed-mode building meets the conflicting needs of air-conditioned and naturally ventilated spaces by optimising different zones to be used at different times. The three subsidery aims guided this research as it transitioned from the wider historic and current context to the history of the case studies and finally the current conditions of the case studies. Because of this, the solution was developed from a holistic understanding of the narrative of unsustainable development as it unfolded in the evolution of the Sudanese house.

10.1. The causes of AC reliance

The Author's original observation of ACs being adopted more rapidly in the last 20 years can be directly attributed to the increase in supply from local production and imports, as discussed in Chapter 4. However, this study suggests that the story of AC reliance started before that, much like a cancer where the symptoms show in the last stages.

The first sign was in the transformation of the traditional house from rural to urban contemporary as it adjusted to smaller plot sizes, fluctuating economic conditions and a social change. This social change included reduced socialisation, reduced security and increased privatisation. The changes were gradual, with each phase changing slightly. However, the contemporary house represented the biggest change in occupant lifestyle and the real beginning of the shift towards an increasingly indoor lifestyle.

The second symptom can be seen in how these factors changed individual buildings during their lifetime. Expats and their introduction of modern air-conditioned villas raised the bar of desirable status, a process called 'standardisation' (Shove, 2003). They also created the initial market for ACs. People in traditional houses started changing materials but keeping the original footprint and way of life. However, the new materials were inefficient, so the occupants had to install fans and ACs to compensate. Initially, these ACs were confined to one or two spaces, but they allowed the occupants to start spending more time indoors. That possibility, in addition to the other socioeconomic factors mentioned before, drove the occupants to increase the number of indoor air-conditioned spaces. Stewart Brand states that individual buildings are shaped by three forces: technology, money and fashion (Brand, 1994). The *technology* in this case, is the availability of new materials and air-conditioning. The *money* is used to fund these changes, and *fashion* is what pressured occupants to upgrade these materials.

Finally, the last step was that these ACs started to be used more intensively by occupants as they spent more time in individual spaces rather than spending the majority of the time together in shared spaces. Increased expectations and the current responses to heat waves further push that consumption level, a trend called ‘escalation’. The expat villas that inspired these changes had occupants who already lived this modern AC-dependent lifestyle from the start. This is why lifestyle in both typologies is now similar, with usage patterns being dictated by the occupant’s age and employment status. The key difference is that the modern concrete buildings responded better to ACs when shaded, giving them an advantage. However, this did not result in reduced consumption levels due to the rebound effect.

Understanding the root causes of a problem allows for more targeted solutions. The Author’s pilot study revealed thermal discomfort in both typologies. This study revealed the socioeconomic reasons that drove the occupants to make these changes and how they led to AC reliance. Understanding the whole narrative of AC reliance allowed the framework to be tailored to address those socioeconomic concerns to ensure its success. This is why it goes beyond just proposing a fabric-first approach to address the thermal discomfort issue, which lies on the surface. People’s past behaviours are also important indicators for their future responses. Addressing them also helps avoid unforeseen consequences.

10.2. Shifting from globalism to regional solutions

The key to the traditional Sudanese house's success was the synchrony between the occupants' lifestyle and their built environment. There was always a comfortable place somewhere in the house for the occupants to use throughout the day. The building also met its occupant's intangible aspects of lifestyle, and their traditional values, such as conformity, socialisation, privacy, and segregation. The harmony cannot entirely be attributed to the building; it is likely that occupants also adapted their lifestyle to the building's capabilities, for example, they used portable furniture to move to follow the shade. As mentioned in chapter 2, this is instinctual as people seek more comfortable areas even within the same room. Adaptive behaviours were ingrained into people's daily routines. The traditional lifestyle allowed for a strong connection with the outdoors.

This balance was disrupted at several different levels. Firstly, on the building level, the change of materials disrupted the daily internal thermal patterns. The reduction of yard quality and quantity further reduced the availability of comfort zones. The occupants also changed their lifestyle, they spent more time indoors, particularly in bedrooms. Adaptive behaviours were no longer a part of everyday life, thus provisions were not made for them. The AC enabled staying indoors longer and disrupted people's habituation to heat, making them more detached from the outdoors and reliant on ACs. The Optimised mixed-mode building is an alternative response to AC reliance because it re-establishes the harmony between the internal built environment and the occupant. It is a modern interpretation of a vernacular principle: thermal migration.

The culturally contextualised thinking that underlies this research is needed in Africa and other developing countries to tackle AC reliance. As mentioned in section 5.6, many components of vernacular architecture served a cultural purpose in addition to their environmental ones. By abandoning vernacular architecture, thermal diversity and local responses to climate, in favour of standardised air-conditioned spaces, both the cultural and environmental nuances are lost.

The trend of rediscovering historic environmental control features (Lawrence, 2020) has recently been accelerated by increasing adaptive thermal comfort research. The adaptive thermal comfort model has challenged equating comfort with static interior environments regardless of location and context

(Lawrence, 2020). This contrasts with the singular worldview advocated by the HVAC industry towards standardised air-conditioned buildings designed to be comfortable based on studies focused on white men in the 1960s (Roaf & Nicol, 2022). In the thermal comfort industry, like most social sciences, standards are built upon research conducted in WEIRD countries (Western, Educated, Industrialised, Rich, Democratic) (Hendriks et al., 2019). The narrow bands of comfort dictated by how the PMV method was used (Roaf & Nicol, 2022) are hard to achieve with passive methods, as seen in the Tanzania case study. The AC is intrinsically linked to international modernism and colonialisation, even if the recent increase in adoption is accelerated by local change (Chang & Winter, 2015).

10.3. The role of socio-technical research in Architecture

Awareness has increased in recent years around the role of occupants in buildings, with many advocating for the upgrading of the passive term occupant to inhabitant to reflect their active role (Cooper, 2018). However, most building science methodologies still focus on buildings physics. More socio-technical research is needed to create new methods to understand the ‘interactive adaptivity’ and ‘co-evolution of the physical and social’ in building performance (Lowe et al., 2018).

This research utilised a holistic understanding of the houses’ performance in Khartoum, addressing occupant behaviour, technology and building fabric across time. In architectural research, this represents a move away from what Fionn Stevenson described as ‘simplistic simulations of single issues’ (Samuel & Dye, 2015, p. 10). It would not have been possible to construct this framework without the socio-technical research that established the evidence base to support it. Chapter 2 detailed how the Sudanese house functioned and showed how previous versions of the Sudanese house met the complex and evolving needs of the occupants and why it is important to build upon that evolution rather than impose a foreign typology. Chapters four, five and six provided the socioeconomic criteria that need to be met for the typology to work, such as providing the ability to expand, maintaining occupant privacy and segregation in the zones. Finally, chapters seven and eight defined the current usage and thermal patterns needed to synchronise when spaces were most comfortable with when occupants used them most.

The mixed-mode methodology used in this study could be used by other researchers working with developing countries. It helped triangulate data to overcome the limited documented and archival information available. The other issue was the extreme climate and theft that led to the loss of information from data loggers. They had to be checked monthly and replaced whenever they were faulty.

The literature review used in the wider context was predominantly from primary sources like studies documenting conditions in the 1970s, colonial publications from the 1900s, various census reports and annual import reports spanning 40 years. Due to the lack of documentation, the information gathered had to be supplemented by interviews with experts in the field.

The second phase was collecting information about the building and occupants' past, once again, there was no documentation available, even for buildings designed by architects. Therefore the researcher relied on extensive and frequent interviews. In many cases, the information had to be crosschecked by additional interviews with other occupants as it relied on their recollections. The researcher also relied on visual aids and logs during the interview (see appendixes A3-A6) to fill out the information in front of the interviewees. This helped the interviewees correct any misinterpretations and confirm their statements. The occupants also revealed vital information as the researcher casually conversed with them during the building surveys and monthly updates; this highlights the strong ethnographic aspect of the research.

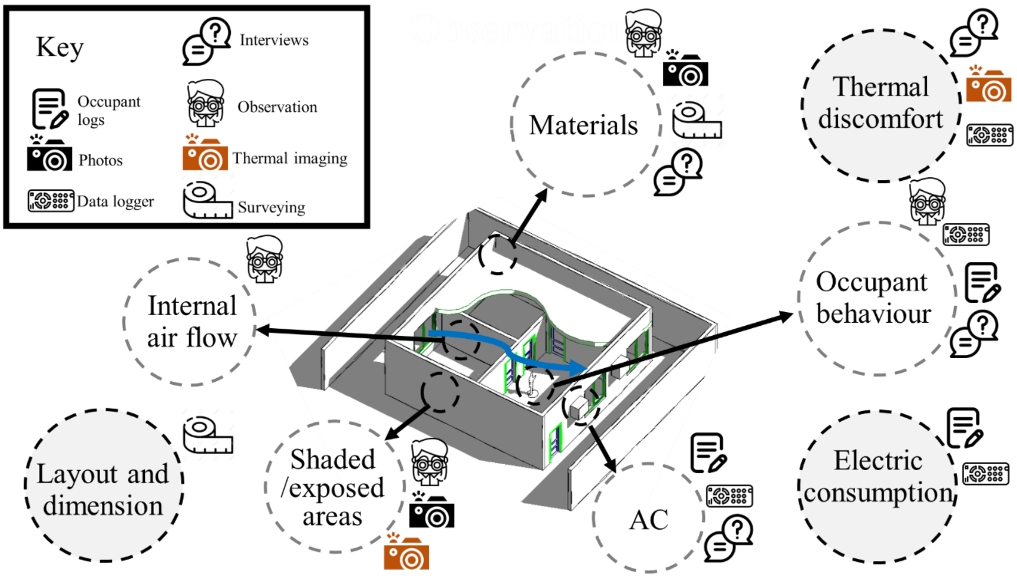

Figure 10.1 The qualitative and quantitative methods used in this research to triangulate information

In order to obtain information about the current situation in the buildings, several techniques were used to triangulate information. To document occupant behaviour, initial interviews and observations outlined the most used spaces and the occupant's daily patterns. This was then confirmed by an occupant log used over two days. As data loggers were limited, this allowed strategic utilisation of them in the most used spaces. Within the data loggers, several types were used to verify the information. For example, to document space use, three types of loggers were used. AC loggers documented when the AC was turned on, motion loggers documented when people moved within the space and carbon loggers dioxide indicated the increase of carbon dioxide due to space occupation. The choice of using one or more of these types in each space was made based on the information gathered from the initial interviews.

Similar to data collection about the building's past, interviews were conducted frequently to verify information obtained through other means. For example, anomalies in the data collected by the data loggers were checked out by asking the occupants. This included a month where there was an increase in use of a space, which turned out to be a lodger staying for a month then leaving. Another example would be that the thermal imaging revealed in a wall had two different thermal profiles. The occupants explained that this was originally a low boundary brick wall; it was converted into a room by increasing height using a cheaper material. Thus providing more context to understand not only why the wall was different, but also the reasoning behind their choice.

10.4. On Practice and Theory

'.....that architects who have aimed at acquiring manual skill without scholarship have never been able to reach a position of authority to correspond to their pains, while those who relied only upon theories and scholarship were obviously hunting the shadow, not the substance. But those who have a thorough knowledge of both, like men armed at all points, have sooner attained their object and carried authority with them....' Vitruvius in The Ten Books on Architecture (Pollio, 1999).

Socially motivated architectural research empowers people to 'design for change' (Samuel & Dye, 2015). In this research, that change is the ability to meet people's modern social and economic needs with a reduced environmental impact. This research did not stop at documenting the status quo, as it provided a tool for action: a research-based methodological framework. The framework conveys to practitioners how they can apply the theory behind the typology to their designs, making it more likely be adopted and, thus, more likely to have an impact. This is important because practice often disregards research, especially when its value is not clearly communicated in monetary terms (Lucas, 2016). Another challenge in applying architecture research is that it needs to meet the rigorous scrutiny of academia yet still be relevant to the industry (Schoenefeldt, 2018).

A key reason this research could find a pragmatic solution was the equal emphasis on historical and current architecture. Had the study been solely focused on the historical only, it would have led to theoretical solutions of ways to reinterpret it. Without the knowledge gained from the existing situation, it would be hard to know which reinterpretation is best suited to solve the current problems. Secondly, the exercise of modifying the two case studies to become optimised mixed-mode buildings allowed the development of the practical framework. This was done by retracing the steps used by the Author to modify the two case studies to identify which pieces of information were the most critical to reach the final design.. It helped that the case studies already had an extensive amount of empirical evidence for the researcher to choose from. However, it would be unrealistic to expect a practitioner to collect that much information, which is why it is necessary to show them what to focus on in data collection for live projects.

10.5. Limitations

Parts of the research was affected by the Covid-19 pandemic and political turmoil in Sudan due to a popular uprising. The lockdowns continued from April to July 2020, which is after the pilot study was completed and before the full-year of monitoring started, so the impact on user behaviour patterns should be minimal. However, the energy consumption was tracked for three continuous years, which includes the lockdown period. An unusual increase in consumption is expected during that period due to increased time spent indoors.

A planned survey had to be cancelled due to difficulty travelling in Khartoum during the study. The survey could have been used to identify how representative the case studies are regarding space use patterns and building history. The case study number was limited to five due to financial restrictions from the number of available data loggers and practicalities, such as the time available to perform the study in Sudan during difficult travel conditions.

10.6. Future work

The study created a framework that can be verified by applying it in live design projects. This will help fine-tune it by creating more specific guidelines for different scenarios based on case studies and surveys to understand the frequency of each case. Simulation can also help create more refined criteria for each zone, such as specifying which volumes are more optimal or the volume per person for a day-ventilation space. Finally, as the solution heavily depends on occupant behaviour, post-occupancy studies will be needed to identify if the users will use the building as intended or if changes need to be made. Once verified, the solution can be implemented in a government program by building pilot projects to set a precedent and popularise the concept within Khartoum and other major cities in Central and North Sudan. The pilot projects need to include new builds and retrofits to allow a wider adoption into the building stock.

10.7. Final remarks

This research has real world implications at three different levels of interpretation. Firstly, the framework can be used as it is to change how houses are designed in Khartoum to make them sustainable. The second level is the concept of zoning in itself. It can be broadly applied to the global south as an alternative to an ‘all or nothing’ response to designing sustainable homes given limited resource availability. Finally, in the broader research realm, it represents a new holistic way of critically appraising vernacular architecture in a way that allows for abstract reinterpretations to solve modern problems.

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Appendix A: Interviews with case studies

A.1. Participant Sheet (for case studies)

House development in Sudan

The study aims to understand how Sudanese houses developed in terms of construction and occupant behaviour in order to understand how this has impacted their usage of air conditioners. Your household has been chosen as a candidate for the study as you fit the demographic profile this study focuses on. If you are interested in participating in the study, the following program will be implemented:

Day 1: 3 hours (a Wednesday or Friday)	**Day 2: 2.5 hours (a Saturday or Monday)**
1. Introduction: 15 minutes 2. Walk around the house to observe any problems and record them. A thermal camera will be used, and pictures will be taken: 30 minutes 3. Data loggers will be installed in 3 spaces on the wall: 30 minutes 4. Measurements of the house's rooms will be taken: 30 minutes 5. Interview 1: 1 hour 6. You will be given a space use log to be filled out in 2 days (either Thursday and Friday or Saturday and Sunday): 15 minutes	1. Interview 2: 1 hour 2. Break and Collect space logs: 30 min 3. Interview 3: 1 hour

Please select which days are suitable for you within March. The aim of the specified days is to give you a sample weekday and weekend to fill your space use log.

If a thermal data logger is placed in your home, please make sure it is not damaged or tampered with until it is retrieved. It will be used to log the temperature and humidity inside your house for the duration of 1 month.

This project is part of a PhD research for the university of Kent and has been approved by the Faculty of humanities research ethics advisory group (REAG). Participation is voluntary and you can withdraw at any moment if you feel uncertain. Your names will be anonymised on the digital records stored on the researcher's laptop unless you request otherwise. The study will help you become aware of the thermal problems in the houses and give advice on possible solutions to implement.

If you have any questions regarding the research, would like to withdraw or would like to see the research results please contact the researcher Huda Elsherif by email at hzte3@kent.ac.uk

If you have any complaints, please contact the Faculties Support Office: fsoethics@kent.ac.uk

Thank you for your participation

A.2. Semi structured interview guide-1

Question:	√	**Looking for (probes):**
1. Tell me about your family history prior to living in this house?		How they lived: Day to day activities – especially cooking
		How they lived: Sleeping arrangements
2. Tell me about the beginnings of this house		The thought process that lead to this house's design
		What did the first layout look like: Plan
		What did the first layout look like: Materials
3. Can you describe who the occupants were in this house and how you used to live when the house was first built?		Who lived in it
		How they lived: Day to day activities - especially cooking
		How they lived: Sleeping arrangements
		How they lived: Cooling methods
4. Here I have two plans that show the house when it was first built and its current state today, can you walk me through this transition?		What/when/why: House materials and plan
		What/when/why: Day to day activities - especially cooking
		What/when/why: Sleeping arrangements
		What/when/why: Cooling methods
		How has being an expat impacted your lifestyle in Sudan?

A.3. Sample interview with a Female Gen X occupant in T2

Family History questions	
Interviewer	Can you tell me about your family history?
Occupant	In the past it used to be my parents, two brothers and six sisters.
Interviewer	So 10 occupants in total?
Occupant	Yes, if you count my parents. My older sisters got married and each one left. Sister 1 and sister first then my brother 1. He got married and separated his family. So then it was just me, and my three sisters.
Interviewer	When was this?
Occupant	After the 1980s, it was us four and my parents, so six occupants. Then my sisters also got married and my brother left for KSA. I remained with my parents with my nieces and nephews from my oldest sister. They grew up with us. Their parents also lived with us until they built their own home. But the kids remained with us.
Interviewer	When was this?
Occupant	Around the 1990's
Interviewer	So it was similar to a typical Sudanese family growth pattern?
Occupant	Yes, very typical.
House history questions	
Interviewer	Let's start from the beginning, when this house was first constructed, how many rooms did it have?
Occupant	I was born in this house. Around 1964. It had one room and a kitchen and sanitary facilities. They used to be separated into a bathroom and toilet.
Interviewer	Ah, was it the type where you had to drain the grey water with a bucket?
Occupant	No no, we had a well, above it there was a concrete floor.
Interviewer	Yes, that type of toilet is still common in rural areas.
Occupant	The house changed even before my brother travelled to KSA. Around the beginning from the 1990s. First, we had three rooms. Then after my other brother went to kuiwat. We changed the house from mud to brick. We demolished it all and rebuilt it.
Interviewer	Did you rebuild it as is or extend it?
Occupant	Yes, there was an extension.
Interviewer	Which areas?
Occupant	It became three rooms, a saloon, two verandas, a store and a modern kitchen. The toilet was modernised too with a septic tank system.
Interviewer	Your old kitchen was outside the house, did you incorporate it during the rebuild?
Occupant	No, it was still outdoors. Out in the yard.
Interviewer	Where the two verandas open or closed?
Occupant	They were open.

Interviewer	Dd you have a mosquito mesh in it?
Occupant	No, just a small barrier and door but nothing to close it off or mosquito nets.
Lifestyle during the old phases	
Interviewer	How did you used to use it? In the afternoons? Mornings? Evenings?
Occupant	We grew up with an emphasis on privacy and segregation. My parents had their own yard, we girls had a yard, and the boys..
Interviewer	Ah, so each group had their own yard.
Occupant	Yes, they were three. The situation is still the same.
Interviewer	Did you used to sleep in those yards?
Occupant	Yes of course. We didn't even have fans. We had to rely on natural breezes. People used to sleep outdoors, the air was fresh, there was no mosquitos.
Interviewer	There weren't any mosquitos?
Occupant	Not at all.
Interviewer	I heard from my friend that there used to be a mosquito prevention program that involved spraying insecticide from airplanes.
Occupant	Oh yes! I remember that. They used to warn us before they started spraying. People used to listen through the radio. There weren't a lot of TVs. Everything was through radios.
Interviewer	During that time, When did you use the rooms during that time?
Occupant	We used to use the rooms during the midday, we would be at school during the mornings. We'd come home around noon and stay in the rooms until three or four pm. Then we prepare the yards to stay there.
Interviewer	Did that involve spraying the yard?
Occupant	Yes, twice. It used to be just once when it was a bare earth yard but when we put the concrete. We had to do it twice to cool enough by nightfall. Once around 3pm and again later.
Interviewer	So you felt a difference after adding the concrete?
Occupant	Yes, definitely. The sand was cool.
Interviewer	Was there any trees?
Occupant	Yes there was one. In the inner yard we didn't have any. But the ones in the street were always there. My dad planted the left one then central one then the right one. The three outside.
Interviewer	It sounds like a beautiful period in your life, you talk about it fondly.
Occupant	Yes it was, even our family ties were stronger.
Interviewer	What about the neighbours, were you close with them too?
Occupant	It was great. It was mandatory to say good morning to all your neighbours everyday. You could enter houses at any time. The families in the neighbourhood were really close.
Interviewer	When do you feel this started to change?
Occupant	People's situations have changed. The economic situation changed too, it changed people's behaviours.
Interviewer	Was this the 1970s crisis?

Occupant	No no, this was after that, after the 1980s. Families became more extended. The house that had three or four occupants now had many.
Interviewer	Do you mean people no longer had time and resources to maintain their social life?
Occupant	Yes, there was no more time for that. Everyone is too busy trying to make a living.
Interviewer	So you're saying that easier access to money in the past helped people have more time?
Occupant	Yes, we had a lot of free time.
Building and AC changes	
Interviewer	Can you tell me when you introduced fans?
Occupant	After we rebuilt the house, at the beginning of the 1990s, we added the fans.
Interviewer	What about the ACs?
Occupant	I'd say the early 2000s
Interviewer	They were all evaporative coolers?
Occupant	Yes.
Interviewer	Have you changed how you use them? For example, did you use them more frequently or less in the past?
Occupant	We started with just one.
Interviewer	In which room?
Occupant	In the middle room (NC.BD). Then we got another one in this room. we depended on it (the first one) because its in the centre of the house. It used to cool the entire house because the house was sealed. Then we bought one here (SW.BD) and in the saloon (NE.BD).
Interviewer	That one was for guests right?
Occupant	Yes, guests and boys. They're still separated till now as a distinct section.
Interviewer	What was that room (SW.BD) used for in the past?
Occupant	In the past, that was my parents room.
Interviewer	Ah, so it was the master bedroom. Were they still using it when you installed the AC?
Occupant	No, just fans.
Interviewer	Oh, so what how was it used as after the AC was installed?
Occupant	It wasn't used frequently at all, because people didn't use it much. In the morning it was cool anyway, but midday or if it is a hot night, yes, we did use it.
Interviewer	Did the room have a designated user?
Occupant	No, it was just the 'girls' room.
Interviewer	Generally, do you feel your use changed ?
Occupant	Not really, now its winter we don't use them much. Two don't work anymore. We only use the saloon and veranda one now. They're four in total.
Interviewer	Yes, I've heard they frequently break down.
Occupant	Yes, especially the evaporative coolers, they have a lot of problems. You have to replace the straw and the pump frequently. Unlike in split units or window units.

Interviewer	So this was the girls room, is it still that?
Occupant	No, its mostly a guest room now.
Interviewer	Is there a difference between how you use the AC from your parents or children? Is there any generation difference?
Occupant	Yeah, its different. The current generation wants the AC to be turned on all the time.
Interviewer	They don't feel comfortable without it? Could it be because they grew up with it?
Occupant	Yeah, they don't adjust like us. We adapt to any environment. With or without the AC, we don't necessarily need it. On cool nights, fans are enough for us. But they turn the AC on and cover themselves in heavy blankets.
Interviewer	I've heard of that happening in other countries too. OK what about your parents?
Occupant	They never used it at all when they were alive. The humidity bothered their joints. They just used fans.
Past behaviours	
Interviewer	I remember that ache in the joints from my own experience as a child using my grandparents evaporative cooler. Especially because he used to close all the doors. So back to sleeping outdoors, when did you stop that? or do you still do that?
Occupant	Oh no. We never go out these days. Unless there's a powercut and we're forced to. But if there's electricity, we stay indoors.
Interviewer	Can you estimate when that started?
Occupant	I don't know, its been a while.
Interviewer	It might help if you remember who was with you the last times you did it.
Occupant	Well, I guess before 2007. It depends on the weather.
Interviewer	Why did you stop?
Occupant	Mosquitos!
Interviewer	So security was never an issue
Occupant	Yes, our neighbourhood is safe.
Interviewer	In the past, people used to move around that house depending on where it was coolest. For example you'd cut vegetables wherever was cool. But now people specify this is the spot for cooking etc.
Occupant	We've always cooked in the kitchen only or in front of it, but never in the house.
Interviewer	Ok. If someone wanted to take a nap in the afternoon, would they sleep indoors?
Occupant	If it was the evening they'd sleep in the yard where the beds were already laid out. But only after the sun has started going down, say after 5pm.
Interviewer	I mean noon, where would someone sleep if the sun was still high?
Occupant	Indoors definitely. The yard would be too sunny.
Interviewer	Where did you used to receive guests in the past and where do you receive them now?
Occupant	We don't have a problem, sometimes they go all the way to the veranda in the back, sometimes they only stay here in the front hall (NW.L)
Building changes	

Interviewer	Oh, you had the veranda, is it metal or straw roofed?
Occupant	Its metal
Interviewer	Was it always like that?
Occupant	No, it wasn't existent in the beginning, we built it after 2007.
Interviewer	You mention 2007 a lot, is there a significance to that date?
Occupant	Yes, its when my father died.
Interviewer	Ah, so you reference events based on that. What about your mom?
Occupant	She passed away in 2010.
Interviewer	Ok, I've covered most of what I'm looking for. I'd like to draw all the information you've given me and confirm it with you. It's very interesting material and I feel like we really need to document our culture.
Occupant	Yes! Our media isn't reflecting who we are to the world. There are rich information out there, but no one is talking about it. I was watching a show called 'deera ly deera' done in Saudi arabia. It shows the culture and habits of different regions of KSA.
Interviewer	I found archival records about Sudan in colonial publications. They documented the reasoning behind different jiritig practices. Some don't exist today.
Occupant	Yes, foreigners have preserved some of our culture. Younger generations don't even know what 'tibish' is (A local variety of cucumber). We grew up with people selling it everywhere. Its rare now, that's why they don't know it.
Interviewer	So, who built the house in the beginning? Was it your father?
Occupant	Yes
Interviewer	Alone, with no engineers?
Occupant	No, he just depended on the plan he was given when he applied for the plot.
Interviewer	Oh, I didn't know that was a thing.
Occupant	Yes, they gave you a plot with a plan and they tell you how many rooms to build.
Interviewer	Oh, so this is an institutional house directly under a government program
Occupant	Yes
Interviewer	And what was the roof made of?
Occupant	The roof was made of wooden panels.
Interviewer	Just wood? Or was it a traditional roof with mud and straw too?
Occupant	Oh, it was like that at some point but the verandas were always wood. The rooms after we rebuilt were changed to metal but the verandas remained wooden.
Interviewer	IS the wood still there?
Occupant	No, because it became old and leaky when It was rainy. So we changed to metal.
Interviewer	When was the false ceiling installed
Occupant	2015 I think, its not too old.
Interviewer	Why did you install it?

Occupant	Because the metal roof was too hot and it bothered us.
Interviewer	Was that the case with the old roof as well?
Occupant	No no, it was cool. The wood was cool, it just needed a fan and spraying the sand floor.
Interviewer	Oh, the internal floor was sand, that makes sense because the tile would have obstructed the direct connection with the earth. When was it installed?
Occupant	Around 2015
Interviewer	Oh so 2015 had a lot of changes
Occupant	Yes
Interviewer	Did you make any other significant changes in the room sizes?
Occupant	No, we just did material changes.
Interviewer	Why did you install the tiles?
Occupant	There was tiles before but it was concrete. We used to top it with vinyl rolls. But they had to be changed frequently because they'd tear. We found it too expensive, and decided to replace it with tiles.
Interviewer	I remember a similar trend in my grandmother's house, it was vinyl first then changed to tiles.
Occupant	Yes, they must have felt a huge difference. Most houses are like that now. Ceramic is easier to clean and more comfortable.
Interviewer	So, previously you mentioned your brother became an expat. Did that have an impact on you?
Occupant	Yes, a very positive impact. He left for Kuwait in the 1980s before the war. He came back after the war and then to KSA.
Past behaviours	
Interviewer	Do you feel the AC changed your lifestyle? Did it make you use one place more than you did previously?
Occupant	Yes it made us stay wherever it's cool.
Interviewer	You started with one AC right?
Occupant	Yes
Interviewer	It was this middle room right, what was its function?
Occupant	A guest room
Interviewer	I've noticed people tend to first air condition either where the TV is or where their guests are. Did you choose the install it in the guest room because of the guests?
Occupant	Yes, but not just because of that. Its central position let it cool three parts of the house.
Interviewer	Was it that strong?
Occupant	Yes, it was an Aljazeera AC, if we closed all the doors it would be cool from this hall (NW.BD) all the way to the Saloon.
Interviewer	Was it shaded on the outside?
Occupant	No, not at all.
Interviewer	Where was the TV?

Occupant	Outside in the veranda.
Interviewer	Do you mean that open veranda?
Occupant	Yes
Interviewer	Weren’t you worried it would get stolen?
Occupant	Yes, we never had any burglars
Interviewer	When did you close the verandas?
Occupant	When we rebuilt the house in the 1990s.
Interviewer	Why were they closed?
Occupant	Because that was the current trend, people preferred to have enclosed spaces. The dirt and dust were a reason too.
Interviewer	Before you closed it, were you still using it as normal? Or had you decreased using it before that?
Occupant	Oh no, we used it right up until it was closed up.
Interviewer	In one of the houses I’m monitoring the users didn’t use the veranda much, which is why they closed it. You’re telling me that’s not the case with you, correct?
Occupant	Yes, we closed it for other reasons.
Current use patterns	
Interviewer	So how do you use the AC these days?
Occupant	Only when its hot, The girls turn it more often, especially at night. IF they could they’d leave it on all the time.
Interviewer	Do you impose use restrictions on them?
Occupant	Yes, we do. I don’t want them to use it all the time. Especially on cool nights.
Interviewer	Do you feel that your generation views electric consumption differently than younger generations?
Occupant	Yes, sometimes they turn off the AC, fan and lights after they leave. But not always. Its especially important after the new increases.
Interviewer	I’ve heard of those, it’s a huge increase.
Occupant	Yes, it’s a 100% increase. It also includes business electricity. Just one kWh costs 10 pounds now.
Interviewer	Is the pricing system still tiered?
Occupant	Yes, the more you consume the more expensive it becomes. You can save by spending less.
Interviewer	If you give me a meter number, I can track your consumption. I noticed with a few other houses that when they pay later in the month they get significantly less electricity for the same amount of money.
Occupant	Yes, the value isn’t the same. My friend got more kWh by paying 300 pounds compared to one who paid 400. It depends on the total consumption in the month. They need to check the bill. She must have bought more that 600. After 600 kWh, any amount costs 6 pounds per kWh.
Interviewer	How much do you consume?
Occupant	We rarely consume more than 200 kWh, even if the summer it barely reaches 300 kWh.
Interviewer	How do you achieve that, I see other houses consume a lot more than that?
Occupant	Fans also consume, or water pumps. They also consume too.

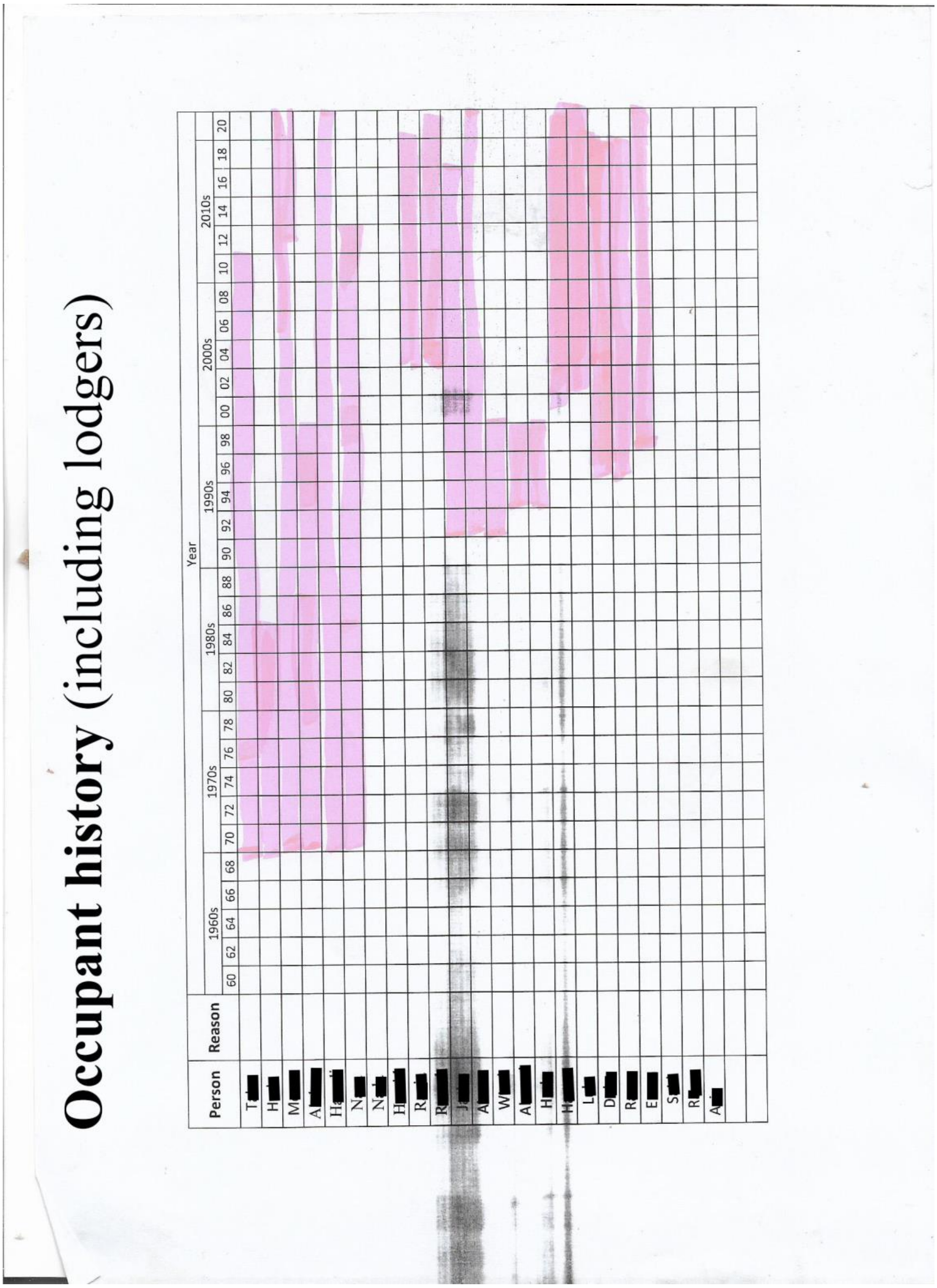
Interviewer	Yeah, especially if you use refrigerants
Occupant	Yes, and deep freezers too.
Interviewer	Deep freezers consume more over time as well, that’s what people use kWh meters for. To find out if old devices consume so much its worth replacing them with someone newer. Especially when electricity is expensive like in the UK.
Occupant	Oh, so you think our electricity is cheap?
Interviewer	Relatively yes, that’s why people focus on reducing consumption. The prices are high to encourage that.
Occupant	I hope people reduce consumption here too after the current increase.
Interviewer	Yes, my supervisor recommended I ask you about your consumption habits after six months of the new prices. So currently how is your consumption?
Occupant	Its very moderate.
Interviewer	How many people live here?
Occupant	Permanently?
Interviewer	Yes permanently. I know in weekends there’s more.
Occupant	Roughly about 8 but not always, Sometimes we gather together with my five sisters. Four are in Khartoum and one abroad.
Interviewer	The interview concluded with the researcher showing the different monitors that will be installed, how they work and what to expect.

A.4. **Occupant day log sample**

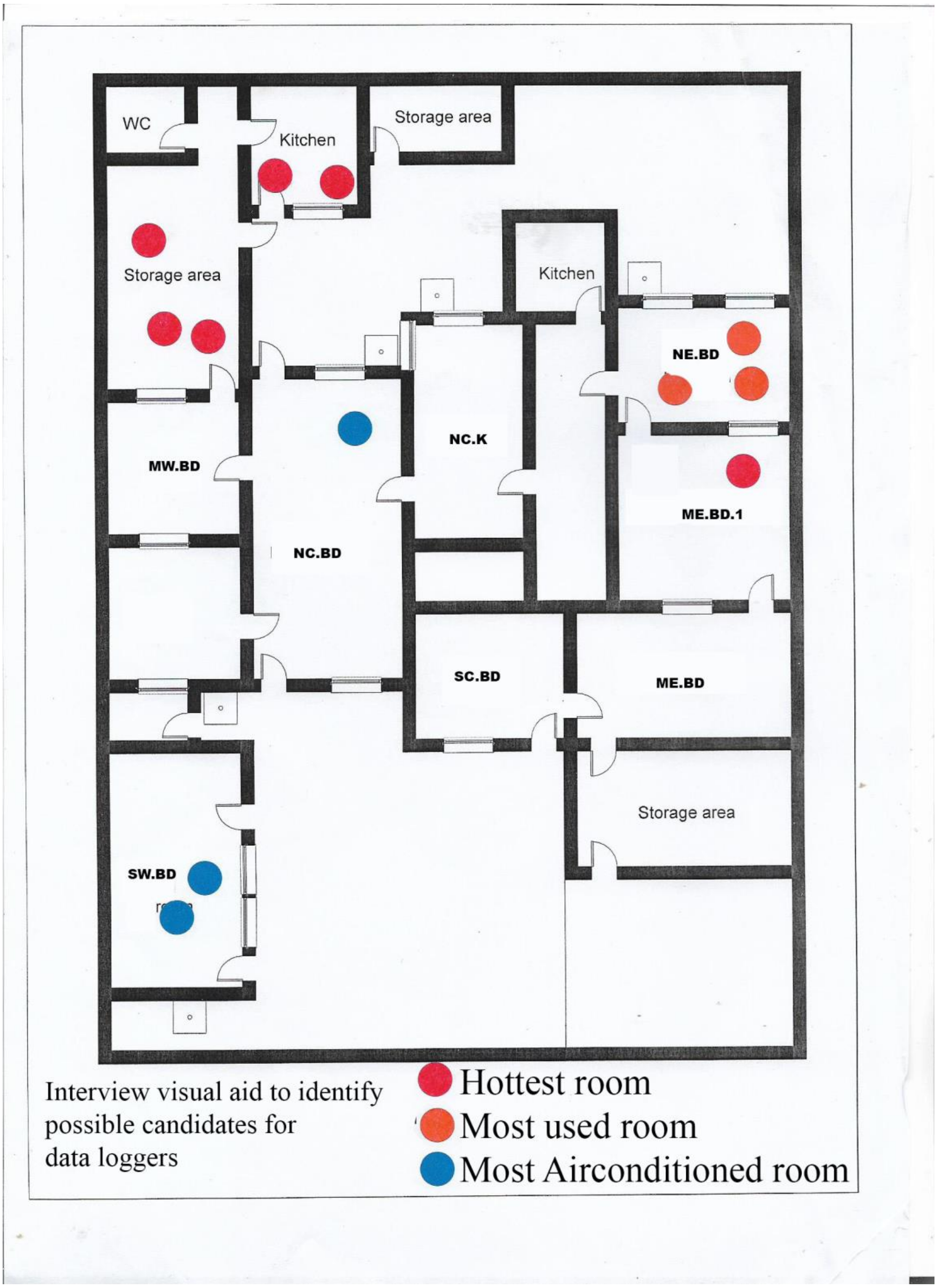
الخميس

	In the morning AM في الصباح												In the evening PM في المساء											
	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11
FGen X 1																								
F Gen X 2																								
M Gen x																								
F Gen Z 1																								
F Millenial																								
F Gen Z 2																								
F Gen Z 3																								
M Millenial																								

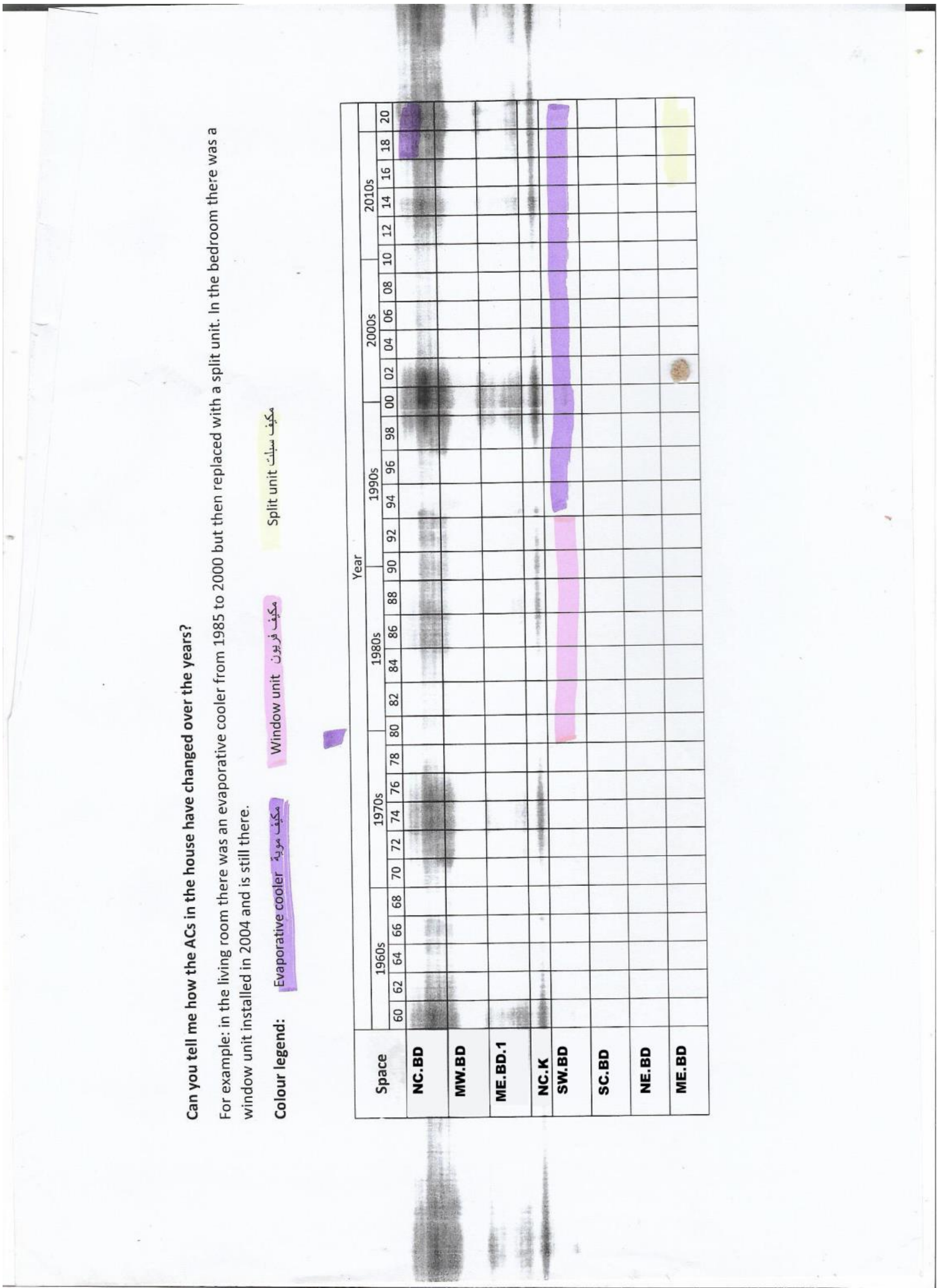
A.5. **Occupant history tracking**



A.6. **Data logger placement pilot**



A.7. AC history



Can you tell me how the ACs in the house have changed over the years?

For example: in the living room there was an evaporative cooler from 1985 to 2000 but then replaced with a split unit. In the bedroom there was a window unit installed in 2004 and is still there.

Colour legend: Evaporative cooler مكيف موية Window unit مكيف فريون Split unit مكيف سبلت

Space	60	62	64	66	68	70	72	74	76	78	80	82	84	86	88	90	92	94	96	98	00	02	04	06	08	10	12	14	16	18	20
	1960s					1970s					1980s					1990s					2000s					2010s					
NC.BD																															
MW.BD																															
ME.BD.1																															
NC.K																															
SW.BD																															
SC.BD																															
NE.BD																															
ME.BD																															

A.8. **Electric purchase logs**

Code	Office	Quantity[KW]	Amount	Purchase Date
3721-0943-3865-1785-8758	THIRD-PART	906.50	340.50	2020-08-01 16:26:19
1959-2195-2698-5784-0213	THIRD-PART	1024.20	440.50	2020-07-02 20:36:29
2857-5849-3581-4389-0801	THIRD-PART	1024.20	440.50	2020-06-01 04:56:49
1760-0007-4429-3963-1525	THIRD-PART	1024.20	440.50	2020-05-03 18:58:34
2634-5690-5800-5565-8516	THIRD-PART	781.80	240.50	2020-04-09 18:54:31
7344-9246-7176-1524-5394	THIRD-PART	582.90	140.50	2020-03-13 10:14:37
3378-1389-4498-4509-7061	THIRD-PART	906.50	340.50	2020-02-05 20:20:26
2188-0929-2247-8264-0831	THIRD-PART	781.80	240.50	2020-01-06 08:19:22
6230-6967-0140-7567-4228	THIRD-PART	35.30	30.00	2019-12-29 10:11:46
0812-3175-3639-4970-9943	THIRD-PART	1024.20	440.50	2019-12-05 09:40:46

Appendix B: Data logger information

B.1. Master template for data loggers

		OUTDOORS		M1												M2		
		Temperature	Humidity	Power on	Temperature	Humidity	AC on	AC on day avg	Temperature	Humidity	AC on	AC on day avg	Temperature	Humidity	Carbon level Occupancy	Power on	Temperature	Humidity
Day	Hour	External	External	MT	MT-1.NW.BD	MT-1.NW.BD	MT-1.NW.BD	MT-1.NW.BD	MT-1.NC.BD	MT-1.NC.BD	MT-1.NC.BD	MT-1.NC.BD	MT-1.NC.BD	MT-1.NC.BD	MT-1.NC.BD	MM	MM-NW.BD	MM-NW.BD
01/03/2021	00:00	24.61	14.28	1.00	27.24	20.88	0.00	0.00					27.13	23.73	659.13		26.75	15
	00:15	24.33	14.28	1.00	27.23	21.10	0.00						27.13	24.83	667.28		26.701	15
	00:30	24.10	14.52	1.00	27.23	21.10	0.00						27.12	24.17	654.59		26.701	15
	00:45	23.88	14.52	1.00	27.22	21.10	0.00						27.13	24.39	628.53		26.652	15
	01:00	23.66	14.52	1.00	27.22	20.88	0.00						27.12	23.95	649.29		26.652	15
	01:15	23.44	14.75	1.00	27.20	20.88	0.00						27.12	23.95	634.22		26.603	15
	01:30	23.25	15.46	1.00	27.19	21.10	0.00						27.12	23.73	620.00		26.579	15
	01:45	22.98	15.46	1.00	27.19	21.10	0.00						27.12	23.50	620.84		26.579	15
	02:00	22.75	15.46	1.00	27.18	21.10	0.00						27.11	23.50	626.76		26.53	15
	02:15	22.52	15.46	1.00	27.17	21.10	0.00						27.11	23.28	623.46		26.579	15
	02:30	22.38	16.17	1.00	27.15	21.10	0.00						27.10	23.28	616.15		26.579	15
	02:45	22.17	16.64	1.00	27.13	20.88	0.00						27.10	23.06	643.67		26.579	15
	03:00	21.99	17.11	1.00	27.11	21.10	0.00						27.09	23.06	620.84		26.505	15
	03:15	21.84	17.11	1.00	27.08	21.10	0.00						27.09	22.84	618.84		26.481	15
	03:30	21.64	17.58	1.00	27.07	21.10	0.00						27.08	22.84	604.55		26.407	15
	03:45	21.46	18.53	1.00	27.05	21.32	0.00						27.08	22.84	601.78		26.383	15
	04:00	21.24	18.76	1.00	27.03	21.32	0.00						27.08	22.84	585.02		26.31	15
	04:15	21.11	18.29	1.00	27.01	21.54	0.00						27.07	22.84	615.15		26.188	15
	04:30	21.02	18.29	1.00	26.99	21.54	0.00						27.06	23.06	580.71		26.066	15
	04:45	20.89	18.53	1.00	26.97	21.54	0.00						27.06	22.84	550.19		26.066	15
	05:00	20.72	18.76	1.00	26.95	21.54	0.00						27.06	22.62	526.75		25.968	15
	05:15	20.56	18.76	1.00	26.93	21.76	0.00						27.06	22.84	527.75		25.871	15
	05:30	20.36	19.23	1.00	26.91	20.88	0.00						27.05	23.28	536.13		25.555	15
	05:45	20.22	19.47	1.00	26.88	21.10	0.00						27.03	22.62	551.42		25.433	15
	06:00	20.08	19.94	1.00	26.86	20.66	0.00						27.02	22.40	535.43		25.191	15
	06:15	19.92	20.42	1.00	26.83	20.88	0.00						27.01	21.96	546.81		24.973	15
	06:30	19.77	20.91	1.00	26.79	20.88	0.00						27.00	21.74	512.60		25.118	15
	06:45	19.66	21.16	1.00	26.75	20.66	0.00						27.02	23.06	474.32		25.239	15
	07:00	19.49	21.40	1.00	26.71	20.44	0.00						27.01	23.06	446.87		25.264	15
	07:15	19.38	21.90	1.00	26.68	20.44	0.00						26.99	21.74	432.88		25.191	15
	07:30	19.27	22.14	1.00	26.64	20.22	0.00						26.91	21.08	447.64		25.215	15
	07:45	19.21	22.64	1.00	26.61	20.22	0.00						26.87	19.83	457.64		25.336	15
	08:00	19.21	23.13	1.00	26.58	20.22	0.00						26.73	18.78	443.88		25.433	15
	08:15	19.28	22.64	1.00	26.55	20.00	0.00						26.50	18.36	437.42		25.312	15
	08:30	19.32	22.14	1.00	26.52	19.78	0.00						26.39	18.57	422.51		25.239	15
	08:45	19.56	21.65	1.00	26.50	19.78	0.00						26.42	18.99	0.00		25.385	15
	09:00	19.79	21.40	1.00	26.48	19.78	0.00						26.43	18.15	0.00		25.458	15
	09:15	20.21	20.91	1.00	26.46	19.56	0.00						26.45	18.36	0.00		25.433	15
	09:30	20.75	20.67	1.00	26.44	19.34	0.00						26.46	18.15	0.00		25.506	15
	09:45	21.19	20.18	0.00	26.42	19.56	0.00						26.45	18.15	0.00		25.579	15
	10:00	21.89	19.71	0.00	26.39	19.56	0.00						26.45	19.20	0.00		25.603	15
	10:15	22.73	18.76	0.00	26.38	19.56	0.00						26.51	18.78	0.00		25.676	15
	10:30	23.32	18.29	0.00	26.34	19.34	0.00						26.50	19.20	0.00		25.798	15
	10:45	23.93	18.06	0.00	26.35	19.56	0.00						26.49	19.62	0.00		25.871	15
	11:00	24.71	17.11	0.00	26.35	19.56	0.00						26.52	19.62	0.00		26.017	15
	11:15	24.99	16.64	0.00	26.31	19.56	0.00						26.56	19.62	0.00		26.115	15
	11:30	25.53	15.93	0.00	26.31	19.34	0.00						26.57	18.78	0.00		26.212	15
	11:45	26.15	14.52	0.00	26.30	19.34	0.00						26.58	18.36	0.00		26.115	15
	12:00	26.72	14.28	0.00	26.34	19.56	0.00						26.61	18.57	0.00		26.334	15
	12:15	27.10	13.57	0.00	26.35	19.34	0.00						26.65	18.36	0.00		26.359	15
	12:30	27.44	12.39	0.00	26.32	19.12	0.00						26.68	19.20	0.00		26.383	15
	12:45	27.93	12.63	0.00	26.32	19.12	0.00						26.72	18.99	0.00		24.055	40.8
	13:00	28.60	11.92	0.00	26.35	19.12	0.00						26.75	18.99	0.00		23.333	42.747
	13:15	29.69	10.98	0.00	26.35	19.12	0.00						26.80	18.78	0.00		24.465	36.334
	13:30	31.92	10.03	0.00	26.37	19.12	0.00						26.85	18.78	0.00		24.658	34.835
	13:45	33.03	9.33	0.00	26.43	19.12	0.00						26.85	17.32	435.57		24.827	31.942
	14:00	33.60	9.09	0.00	26.48	18.68	0.00						27.04	15.86	414.66		25.118	27.293
	14:15	34.06	9.33	0.00	26.51	18.24	0.00						27.11	15.44	428.81		25.458	24.261
	14:30	34.35	9.09	0.00	26.56	18.24	0.00						27.13	15.86	422.35		25.506	23.102
	14:45	34.56	8.85	1.00	26.61	18.02	0.00						27.11	16.06	455.87		25.603	24.478
	15:00	34.44	9.09	1.00	26.65	18.02	0.00						27.06	16.06	469.25		25.798	21.319
	15:15	33.10	9.56	1.00	26.70	18.02	0.00						27.05	16.27	457.64		26.09	15.848
	15:30	32.47	9.80	1.00	26.74	17.80	0.00						27.03	16.06	460.40		26.334	15
	15:45	32.25	10.27	1.00	26.81	17.58	0.00						27.02	16.90	450.26		26.31	15
	16:00	32.26	10.27	1.00	26.84	18.02	0.00						26.97	17.95	449.41		26.603	15

Appendix C: Experts interview

C.1. Participant Sheet (Civil servants)

House development in Sudan

The study aims to understand how Sudanese houses developed in terms of construction and occupant behaviour in order to understand how this has impacted their usage of air conditioners. achieved. As a civil servant in the ministry of planning in Khartoum, It Is kindly requested that you take part in this questionnaire. It will take approximately 10 minutes to fill out the one-page questionnaire. The questions aim to collect information about informal development in Sudanese houses and challenges faced by planning committees to enforce the law.

This project is part of a PhD research for the university of Kent and has been approved by the Faculty of humanities research ethics advisory group (REAG). Participation is voluntary and you can withdraw at any moment if you feel uncertain. Your names will be anonymised on the digital records stored on the researcher's laptop unless you request otherwise. The study will help you become aware of the thermal problems in t houses and give advice on possible solutions to implement.

If you have any questions regarding the research, would like to withdraw or would like to see the research results please contact the researcher Huda Elsherif by email at hzte3@kent.ac.uk

If you have any complaints, please contact the Faculties Support Office: fsoethics@kent.ac.uk

Thank you for your participation

Huda Elsherif

Appendix D: Practical framework

Appendix D:

An architect's guide to sustainable urban houses in the Global South

Huda Elsherif

University of Kent

ABSRACT

A short guide to help architects design houses that are socially, economically and environmentally sustainable in the challenging context of the Urban global South.

Contents

About

A sustainability consultant and researcher with expertise in thermal comfort, building physics and social sciences. After conducting 4 years of research in Sudan looking at the increase in AC reliance due to modern buildings, I created a framework for designing sustainable houses in Sudan. I decided to distil and generalise these findings to create a guide for architects designing sustainable houses in the global south. The guidance is aimed specifically at urban contexts in developing countries, where occupants live consumptive modern lifestyles but there is limited resources to design and build highly efficient buildings.

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Part 1: Introduction

The challenges in the Urban Global South

Housing studies in the global south typically focus on the poor, which form the majority of the population. However, the urban middle and upper classes often consume more than this majority due to economic inequalities.

This class poses a unique sustainable design challenge as they have the expectations and habits of developed countries with the available resources of developing countries. This means that local low tech solutions such as stabilized soil blocks do not meet their social status needs, while high tech solutions are unavailable requiring extensive transportation and high costs. Poor governmental support and regulation further add another layer of complexity.

Designing sustainable houses in this context requires a deep understanding of the local socioeconomic context to find middle-ground solutions.

Figure 1 An informal settlement near an affluent housing scheme in South Africa. Source: Johnny miller

Figure 2 A street in Singapore with Airconditioners lining the walls

Example of the challenges faces by Sudan

Sudan is a least developed country (LDC). The power grid has been increasingly overwhelmed which led to extensive power cuts during the summer, with Airconditioners (AC)'s being a key cause.

Air conditioning in Sudan is linked to social status as it was imported with Mediterranean style villas from the Arab gulf. It has become a status symbol.

The capital has recently undergone extensive urbanisation which has changed the community structure, reducing the sense of safety and community. This changed people's use of outdoor spaces from open spaces, streets and even private yards.

High land prices from the urbanisation have led to increased density. This increased density has led to the increased adoption of multi-story buildings despite the prevalent preference for detached houses with yards.
High inflation rates and embargoes severely limit the availability of imported materials and technologies. Where possible, local materials need to be used as much as possible.

The importance of socioeconomic studies

People's socioeconomic situiation impacts how they design, build and use spaces. With most research focused on developed countries, these nuances are often missed when designing houses in the global south. Understanding them is important because it helps create realistic solutions that holistically meet the occupants needs. This means that occupants are more likely to actually adopt the solution. These socioeconomic needs include privacy, security, gender segregation, family structure and socialization.

These factors need to be viewed both within the physical realm of the neighborhood and building to the intangible aspects of occupant behaviour and wider socioeconomic conditions. These factors are shown in Figure 3.

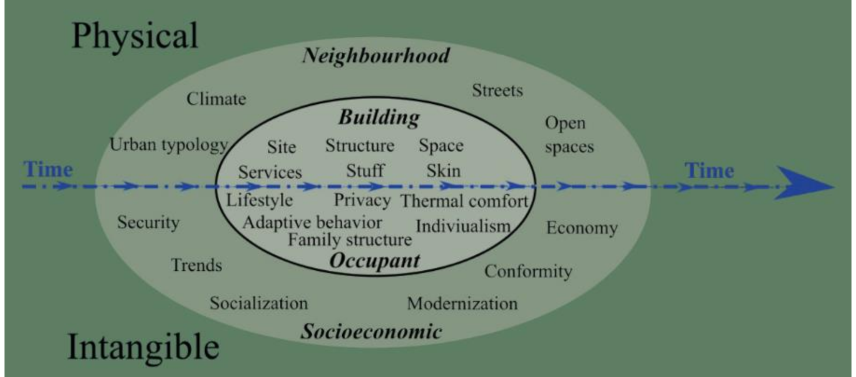

Figure 3 The socioeconomic parameters explored by this research

Case study from Sudan

People in Sudan prefer to live in extended family settings, which means that several different types of occupants use the house. This means the house is always occupied and consuming energy.

People used to live communally and share spaces, but that has become less common due to the increased adoption of modernity and individualism.

Privacy within the house is paramount. Female guests must be segregated from male residents, and male guests must be separated from female residents. Gender stereotypes are strong, with women's activities mainly occurring within the household, such as cleaning and caring for livestock. Men's activities focused on the outdoors, such as going to the market and working. These two factors create an outer public male zone and an inner private female zone.

The frequent power cuts in Sudan have caused people to resort to more consumptive behaviours. These include using a lower setpoint to 'precool' the building, using the AC longer and adding a battery or generator to cope. The pursuit of status has led to people demolishing their high thermal mass mud houses for low thermal mass thin brick walls and uninsulated iron roofs. This makes the houses hot during the day and warm at night.

All of these factors are examples of socioeconomic factors that might impact the design of the house and need to be accounted for in environmental solutions.

Figure 4 A photo showing a traditional house in Khartoum city

Part 2: Reinventing vernacular concepts

Vernacular architecture met people's socioeconomic needs within the available materials and local climate. The wealth of information in them could be reinterpreted into modern solutions. This guide proposes one such solution which is repurposing thermal variety and thermal migration. Through explaining how it was upgraded, this guide hopes to inspire architects to explore how other concepts could be reinvented too.

Thermal lag

In hot arid climates, people use thick mud or stone walls that have high thermal mass. This makes them act like a battery, storing heat during the day. When the 'battery' is full, the walls start to emit that heat into the rooms. This causes thermal lag, which means that the internal temperature peak is delayed from the external temperature peak.

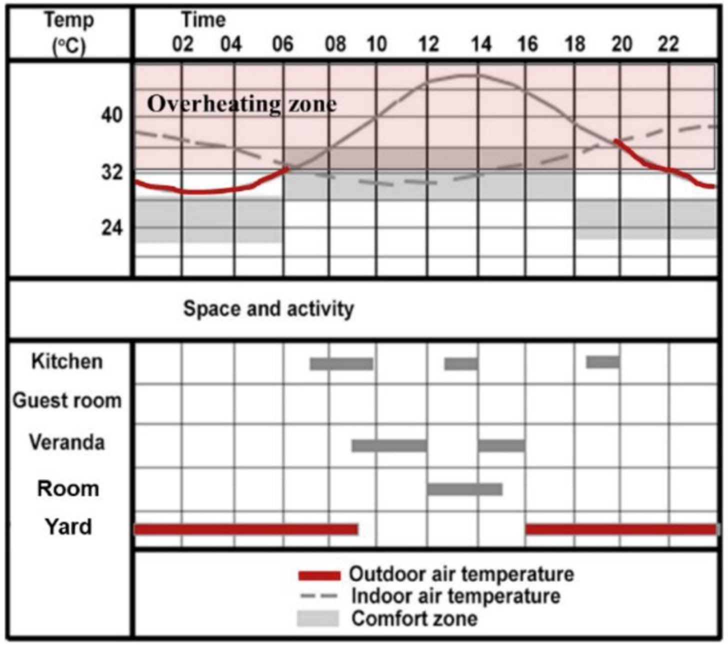

Figure 5 Space use and daily temperatures in a traditional setting.

Figure 5 shows that the outdoor temperature peak is around 2 pm while the internal one is around 11pm. When the outdoor temperatures are cold at night, this heat makes the spaces warm inside. This is called a large 'dirunal swing' when there is a big temperature difference between day and night. However, when the nights are warm, this makes it hot inside at night. Figure 5 shows that it is hotter indoors than outdoors from 8pm to 6am.

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Thermal migration

People adapted to this problem by utilizing the thermal variety of different space types in the house. These include outdoor spaces like different parts of the yard, semi outdoor spaces like verandas and indoor spaces like rooms. The migration pattern in Sudan was horizontal, going from the yard in the mornings to the veranda in the afternoons to the indoors at noon and back to the yard in the evening. In other middle eastern countries, vertical migration meant using the roofs too. Some cultures even specialized rooms for winter and others for summer by changing the materials and shading in the spaces.

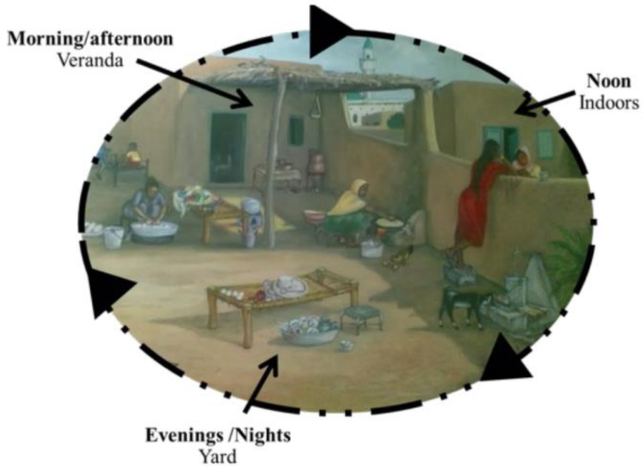

Figure 6 An illustration showing how people migrate through-out the house to utilise thermal variety

Reinterpreting the past - zoning as a solution

Vernacular solutions cannot be blindly copied, because they are usually abandoned for not currently meeting other important criteria, like longevity or convenience. These solutions however can abstractly be adapted to fit modern contexts.

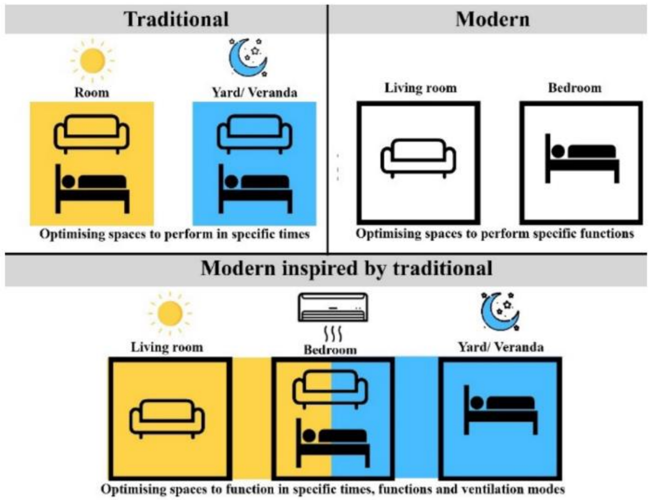

Figure 7 reinventing traditional concepts

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An example of this can be seen in figure 7. In the past, spaces were optimised to be comfortable at different times.

In its essence, the thermal environment synchronised with the occupants use patterns. In modern times, spaces are optimised to serve specific functions, for example, most bedrooms have fixed beds that are hard to move.

These two concepts can be combined together by optimising spaces to function in specific times AND functions. This can be done by reintroducing the thermal variety that existed in traditional houses.

However, thermal migration is now inconvenient because people live more sedentary and private lives. Therefore, the optimising needs to reflect that by respecting the new usage patterns.

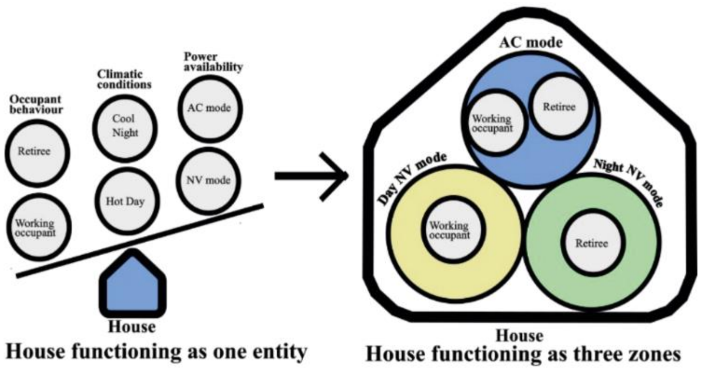


Figure 8 zoning as a concept

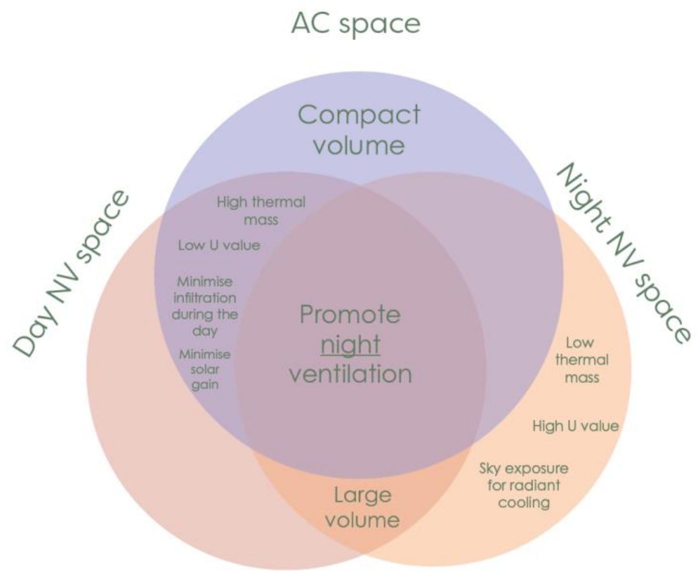
This concept has been coined as 'zoning'. There are many conflicting needs in modern houses in developing countries. In Sudan, these needs are different user types living together, different temperatures throughout the day and an inconsistent availability of power. The idea is that instead of trying to meet all these needs in the entire house, different zones can be optimised to meet a few of them. This way, the zones collectively meet the house's needs.

In Sudan, this meant creating a day natural ventilation (NV) zone, a night NV zone and an airconditioned AC zone. These zones were chosen based on the parameters set in the socioeconomic study. The zones will look different in each context. For example in a hot humid climate where the day and night temperatures are similar for most of the year, the zones can be reduced to an AC zone for heatwaves and an NV zone for mild temperatures. The number of spaces in the AC zones would depend on whether the heatwaves impact day or night comfort and when the house is used. If it is only occupied at night during heatwaves, then the bedrooms need to be the AC zone. If the heatwave only impacts day temperatures, then the living room can be the AC zones.

Optimising zones

An important question that needs to be answered is: how do we optimise zones environmentally? The answer will depend on the climate and when you need the space to be comfortable. The CLEAR website X provides a good starting point in that optimisation. Using the information from the website, figure x shows the needs of the three different zones in a hot arid climate.

The changes you can make are changing the space dimensions, the external fabric, the openings layout, the shading and the exposure to the night sky. By manipulating these elements, you can customize each zone.



15 Figure 9 A comparison of the environmental needs of a free-running and AC building in a hot-dry climate

Figure 10 shows Saini's proposal of a day and night use zone within a courtyard house in a hot-dry climate by varying the thermal mass thickness. The day zone had thin walls and was positioned in the north where it is cooler. Separating the two zones like this also meant efficient cross ventilation at night for both sides, which is a common need for all three zones

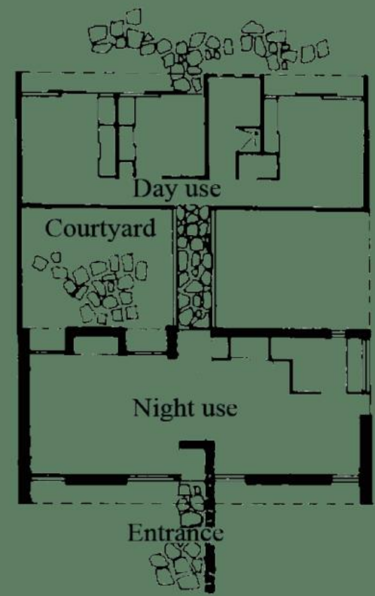


Figure 10 An example of varying using different construction types to create day and night zone. Source: (Saini,1980)

Environmental optimisation must align with socioeconomic needs to be sustainable

The socio-economic information gathered needs to guide the optimisation process to ensure that solutions are holistic. In this example we explain one parameter, which is volume. In an AC zone, a smaller volume is more efficient, however spaces have specific volumes to serve other purposes.

For example, in Sudan rooms were typically 4x4m because that's the largest they could build with traditional materials. The rooms were few and mainly used for storage, which is why they had to be large. The large family size also meant the rooms had to accommodate at least three people. This also impacted the furniture choice as shown in figure 11.

However, in modern bedrooms, rooms are typically occupied by one or two occupants. A desk is also needed for daytime use. This new arrangement can be achieved with a much smaller area as shown in figure 11.

On the other hand, people's psychological comfort and acceptability of smaller spaces needs to be investigated to ensure they don't reject the space.

Another example of socioeconomic need is that security concerns were raised by the occupants. They stopped sleeping outdoors because of the impact of urbanization on rising crime levels. Providing a suitable outdoor space as a night zone is an environmental measure. But to ensure that occupants use it, you must provide that security, for example with a metal grill like the one shown in figure 12. It is also modern looking which will suit the occupants aspirations to keep up with trends, which is another social factor. Adding a mosquito mesh will also help as it is also a concern.

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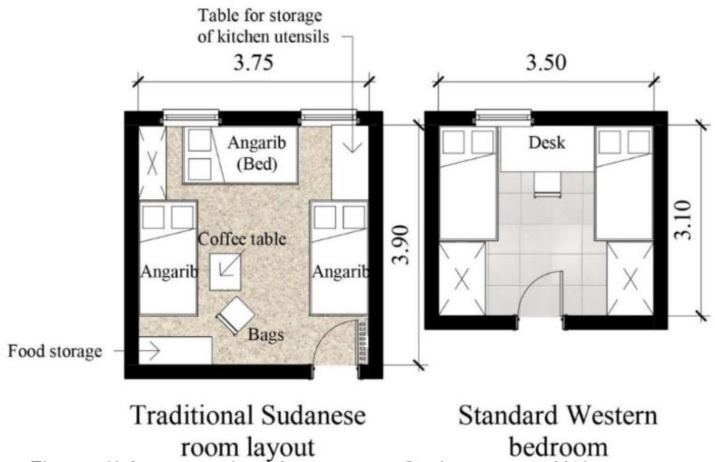

Figure 11 A comparison between a Sudanese and Western bedroom showing the impact of function on size.

Figure 12 An example of a secured patio

Part 3: Framework for the optimised house

After gathering the general socioeconomic information and the local climatic conditions to decide on the zones needed and how to optimise them, this information needs to be applied onto a live project. Each project has its unique conditions that dictate which spaces are best used as which zones.

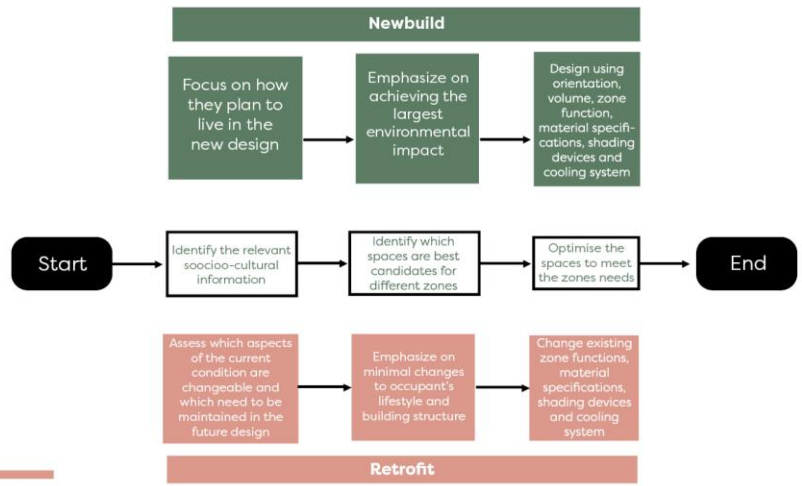

Figure 13 A flowchart showing the steps needed to create an optimised mixed-mode building in both new buildings and retrofits

Figure 13 is a suggested framework for applying the zoning concept on a specific project. The steps differ slightly between newbuilds and retrofits but follow the same principles.

Step 1: Identify the relevant socio-cultural information

You need the number of occupants and when they typically use spaces to estimate how large each zone needs to be. This includes how many spaces and how large each space is within the zones.

People's lifestyle helps you know how many zones you need, it might be possible you need two AC zones for example to cater to two different demographics that can't comfortably share a space.

The family's economic background and their future plans and aspirations helps you create priority goals that the zones need to achieve. For example, their budget might be limited and it may be best to upgrade specific spaces more intensively rather than make small changes throughout the design.

Step 2: Identify which spaces are the best candidates for which zones

The sociocultural information provided in the previous step needs to be translated into design parameters. The key goal is to identify how to allocate each zone within the house. In a new build, the freedom to change spaces means that you can focus on making the largest environmental impact.

Step 3: Optimise the spaces to meet the zones needs

After identifying the spaces for each zone, the designer needs to optimise the space environmentally, while keeping in mind the socioeconomic parameters stated in step 1. This sometimes means going back to step two and changing which space functions as a specific zone. For example, its possible a different room is more likely to be naturally comfortable without air-conditioning due to its orientation or location. This would mean it needs less intervention to optimise it as a day NV zone. This is especially important in retrofits where structural changes need to be limited.

	Key questions	Detailed questions	X
Stage 1	How large is each zone and what are the space sizes, types and quantity?	What is the budget avaliable?	
		How many occupants are there and which spaces do they use?	
		What is the main goal of the optimisation? Is it thermal comfort or reducing electric consumption?	
	How do we optimise the zones?	When is the building occupied and by how many in each phase?	
		Are there special needs that need to be met? An example is power cuts mandating a comfortable naturally ventilated zone.	
		Are there specific climate needs linked to specific times?	
		s there a need for AC for cooling or heating? Is that need daily or seasonal?	
		How do the occupants plan to expand?	
		Can people share zones? Or is there sub divisions based on gender, age or family?	
		Are spaces used communally or privatised?	

Checklist for zone optimisation

	Key questions	Detailed questions	X
Stage 1	Back-ground	What is the budget avaliable?	
		How many occupants are there and which spaces do they use?	
		What is the main goal of the optimisation? Is it thermal comfort or reducing electric consumption?	
	What are the zones we need?	When is the building occupied and by how many in each phase?	
		Are there special needs that need to be met? Like power cuts mandating a comfortable naturally ventilated zone.	
		Are there specific climate needs linked to specific times?	
		Is there a need for AC for cooling or heating? Is that need daily or seasonal?	
		How do the occupants plan to expand?	
		Can people share zones? Or is there sub divisions based on gender, age or family?	
		Are spaces used communally or privatised?	

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Retrofit case study example

T2 was one of the study's case study buildings. It has 2 male occupants and 4 females in an extended family setting. Like many houses in Sudan, it started as a small traditional building with scattered mud rooms, with bare floor walls and wood roofed verandas. It slowly expanded and the building materials were replaced to brick walls and corrugated iron roofs.

The house used to be cool without needing a fan, it just needed to be sprayed with water in the evening. However, the house is now very hot during the day (reaches 40oC!) and warm at night due to lightweight construction. The occupants no longer sleep outdoors due to security and mosquitos.

Existing materials

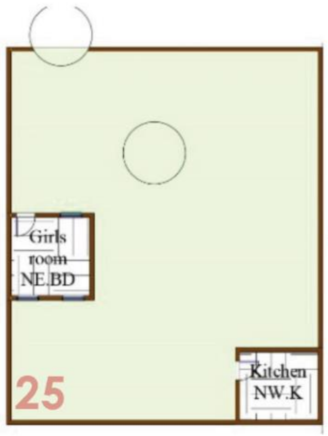
False ceiling

Metal roof

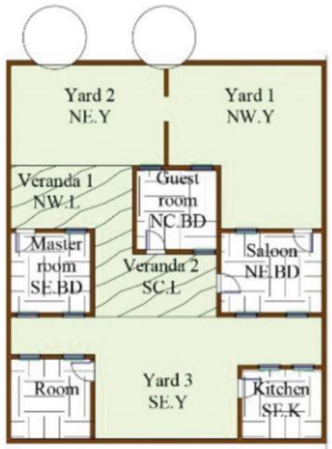
Brick wall

Building evolution

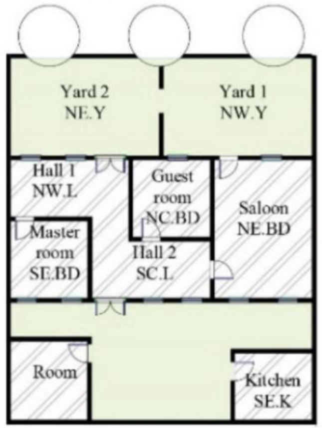
Phase 1: 1964 -1970
Original design



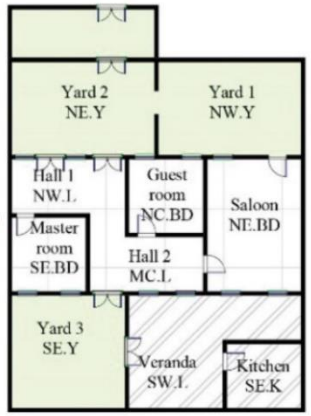
Phase 2: 1971 -1990
Moving in



Phase 3: 1990 -2000
Transition to household



Phase 4: 2000 -2020
Current State



Retrofit case study example
Step 1 and 2

Step 1: Identify the relevant socioeconomic information	Impact on design
The family has a strong male/female divide.	They cannot share one zone
The family lives communually and rooms are not allocated to specific people	There is more flexability in assigning spaces to zones.
Though the occupants intend to demolish the building in the future and rebuild it as a multi-story building, their current thermal condition is highly uncomfortable.	Changes need to be as cost-effective as possible. They also need to focus on improving thermal comfort more than saving energy.
The males use 'the Saloon' for siestas with the evaporative cooler on and open the windows at night.	The Saloon has to serve a dual day/night function.
The two bedrooms are occupied by one sister who uses Ac excessively and the other, who dislikes it and rarely uses it.	Just one bedroom needs to be an AC zone in this case, rather than both, especially given that all females have access to the room.
Someone is always home to guard the house during the day.	There is need for a Day NV space but it doesn't have to be large.
The females spend their day outside the home and return in the evening to spedn time in the closed veranda before sleeping in different places.	The communal spaces that needs to be large enough to accommodate everyone is the night zone in this instance.

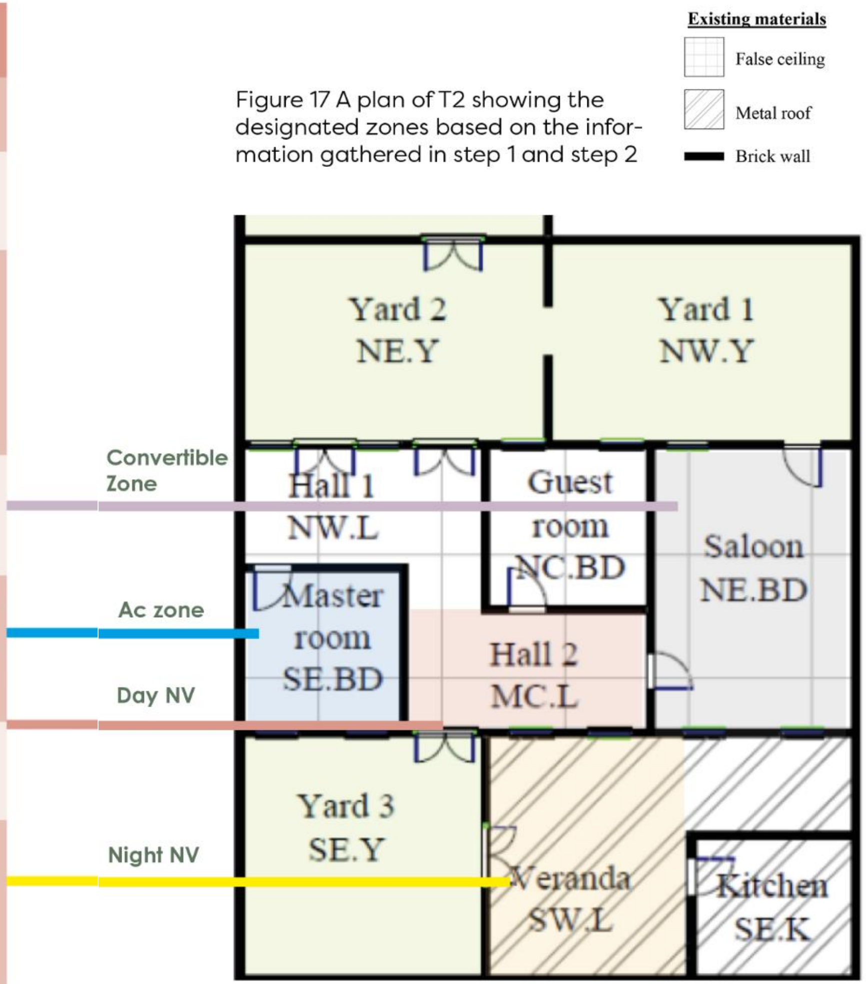


Figure 17 A plan of T2 showing the designated zones based on the information gathered in step 1 and step 2

Step 3: Optimising Spaces

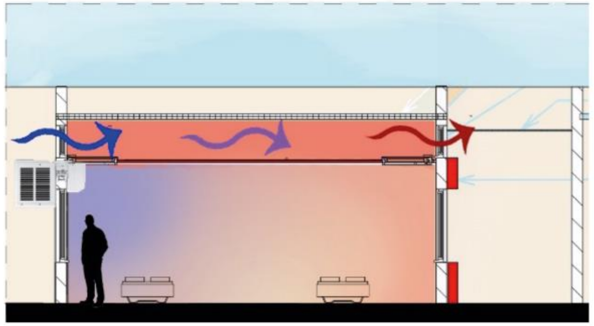
Existing materials
- False ceiling
- Metal roof
- Brick wall

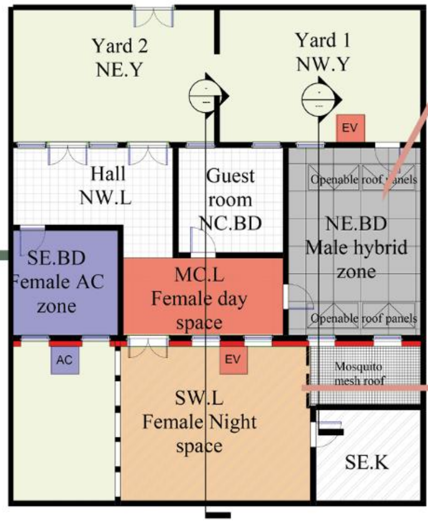
New materials
- Wall insulation
- Open wall with mosquito mesh
- Mosquito mesh roof
- Movable insulated false ceiling panels

Zones
- EV Evaporative cooler
- Day zone
- AC Refrigerant AC
- AC zone
- Night zone

Day NV zone/ AC zone mode

The zone will be scaled during the day AC turned on during the midday siesta



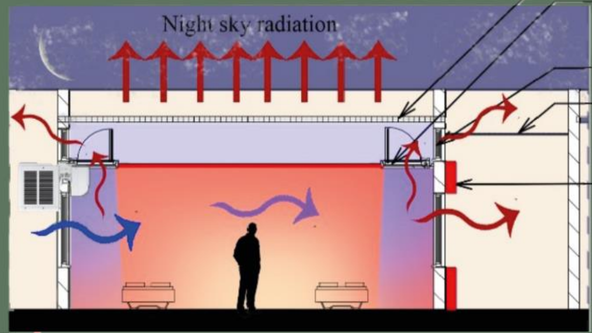


The Day NV zone and AC zone

The southen wall and roofs were insulated to reduce heat transfer in both zones. The volumes were not altered to reduce construction costs.

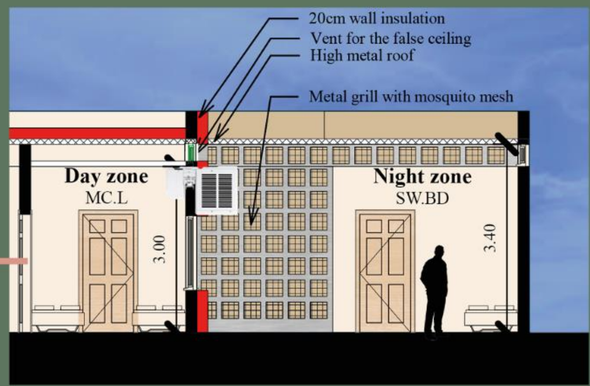
Night NV zone mode

The windows facilitate cross ventilation
Ceiling panels expose the floor the to radiant iron roof



The Night Zone

Veranda was converted back into an open verandan with a metal grill and mosquito mesh to provide saftery. The ceiling height was increased for better cross ventilation



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