Environment: A Bioclimatic Approach to Urban and Architectural Design in Sub-Saharan African Cities

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Abstract Drawn on shared understandings of what "environment" might mean across different disciplines and making reference to the most recent literature on bioclimatic and sustainable urban and architectural design, this chapter aims at providing some general guidelines on how to work with local climate conditions and materials to achieve more sustainable and climate-sensitive building design. This is particularly crucial when dealing with fast-changing urban areas—especially in the sub-Saharan African context—where the climate crisis combined with unprecedented urbanization trends are increasing the pressure on natural environments and resources becoming more and more endangered and scarce. These challenges need to be addressed through a conscious and a cross-scalar approach towards the built environment. The case of Mozambique is adopted as a testbed for the combined use of traditional building techniques and innovative bioclimatic methods adopting basic energy flows—solar irradiation, winds and air humidity, among many others—as main guiding parameters to achieve a better comfort both in new or renovated buildings.

1 Introduction

The definitions provided by different sources of the term "Environment" share the consideration that this concept is a synthesis of several factors that determine the characteristics of a place.

The Cambridge dictionary, defining that the environment is represented by the set of 'air, water, and land in or on which people, animals, and plants live'[1] does not specify, unlike the Merriam Webster dictionary, that the environment modifies the

[1] https://dictionary.cambridge.org/it/dizionario/inglese/environment (Accessed 10 December 2021).

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way an individual or an ecological community lives. The most relevant to this context definition of Merriam Webster dictionary defines the environment as 'the complex of physical, chemical, and biotic factors (such as climate, soil, and living things) that act upon an organism or an ecological community and ultimately determine its form and survival'.[2] Air–water–soil, or climate–soil are the interface elements we deal with: the environment influences the possibility of organisms, animals and plants to exist and organize themselves to survive.

Our survival in a habitat is allowed by the environment. At the same time, it is also true that we have been able to modify the environment by controlling its elements to enable our adaptation to it. Unfortunately, our ability to change the environment has in many cases led to its deterioration: excessive consumption of soil, water contamination, air pollution resulting in climate change and impacts that change our relationship with the environment itself (IPCC 2014).

The concept of "anthropocene" (Crutzen and Stoermer 2000) reminds us that human beings are becoming the major ecological force. For this reason, we are required to take responsibility for the environment.

Besides the policies necessary for protecting the environment and focusing on the topic from the urban and architectural designer's point of view, it is appropriate to include in the definition the possibility to act on the environment itself, with proper methods and considering the factors that configure it. It is a design approach that has to be able to respect and enhance the environment and make it hospitable, liveable and comfortable to the people and living organisms that reside in it and represent the ecological community.

Different approaches are related to the transformation of the environment, such as bioclimatic architecture, sustainable design, design with nature, climate-responsive, etc. They are not mutually exclusive and often pursue the same goal of guaranteeing acceptable comfort conditions for people and maintaining balance with the material and intangible resources in the context. In some cases, the resources can be implemented to improve microclimatic conditions both indoor and outdoor, but sometimes they need to be preserved and protected. Bioclimatic, as defined by the Collins dictionary (2021), is an adjective 'concerning the relationship between climate and living organism'[3] (including buildings). The bioclimatic design approach aims to maximize comfort level by optimizing the sustainability and enhancing the passive solutions, connected to local climate, due to the design of the building envelopes that helps to improve (in the cold season) and control and limit (in the warm-hot season) the heat.

The environmental approach to design—which crosses the different scales of the city and feeds on its interactions—is a cross-disciplinary path that includes the knowledge of the context and the elements, such as materials, vegetation, water, as well as energy flows (i.e. solar radiation), winds, etc. It is also the search for a balance between the elements that find in the urban and architectural project their synthesis.

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[2] https://www.merriam-webster.com/dictionary/environment (Accessed 10 December 2021).

[3] https://www.collinsdictionary.com/it/dizionario/inglese/bioclimatic (Accessed 10 December 2021).

2 African Environment and Mozambique

In the broad context of living in Mozambique and more generally in sub-Saharan Africa, the environment is a concept that includes aspects of fragility, especially concerning a series of epochal changes taking place, including demographic growth of the population and the rural-to-urban migrations.

In 1990, just over 30% of the African population used to live in cities; by 2035, the percentage could rise to 50%, according to the United Nations (UN 2017). This is followed by an immediate and direct consequence of the informal expansion of the small-, medium-sized towns and megacities. The resulting population growth—in general, and more specifically in urbanized areas—is linked to the pressure on the territory due to excessive land use in concentrated areas. Moreover, it is also due to deforestation and natural resources exploitation for the energy supply (UN 2007), representing a threat to ecosystems.

If the way to build in small villages or small settlements still reflects a link between the environment, climate and local materials, in urbanized contexts that are rapidly transforming, this connection is missed. The bioclimatic-environmental approach to design should become a common practice since it is based on local climatic conditions, assuming them to be the fundamental parameter influencing the design choices.

According to this perspective, a broad-spectrum knowledge path has to precede the design process to allow interaction with the place resources and characteristics.

In particular, as regards Mozambique—a country characterized by a long coastal strip that gradually rises towards the inlands until the edges of the great continental plateaus—it is important first to investigate the characteristics of the climate.

According to the Koppen classification, the climate in Mozambique, influenced by the monsoons of the Indian Ocean and the warm current of the Mozambique Channel, is tropical hot (sub-type Tropical Savanna Climate), varying, depending on the region, between dry climate sub-humid and semi-arid. However, it also has several regional variations due to local factors such as altitude, proximity to the coast and latitude.

The northern region is subject to low equatorial pressures, while the south is affected by tropical anticyclones and hot currents in the Mozambique Channel. More precisely, three climatic zones can be distinguished in the territory:

1. North and Centre: monsoon climate, with a dry season of 4–6 months.
2. South: drier climate, with a dry season of 6–9 months.
3. Mountainous areas: tropical climate due to the altitude.

During the year, there are two seasons: the dry and cool season, between April and October, and the hot-humid rainy season, from October to March. From October, the rains begin to intensify until March/April (only in the south, the onset of rains is often postponed) (Fig. 1).

Average annual temperatures vary between 20 °C in the south and 26 °C in the north, with the highest values during the rainy season. The average yearly humidity values (RH%) are, in general, relatively high, ranging between 65% (dry season) and 75% (hot and humid season). During the rainy season, the prevailing winds in the northern part of the State are from the northeast and in the country's southern part from the south.

The effects of climate change have determined in the temperate climate areas advantages in energy consumption and thermal comfort in the winter season (with a reduction in heating needs), despite an increase in cooling requirements. In a tropical climate, the need to minimize heat gains and maximize heat losses represents an increasing challenge throughout the year.

3 Bioclimatic Strategies to Design at the Urban and Neighbourhood Scale

Rapid urbanization, especially in Africa, generates critical issues from the environmental point of view that can be limited only through a conscious and a cross-scalar approach.

A single building does not change the climatic conditions of a city. The ensembles of buildings built according to the international standards, which generally disregard the environmental characteristics of the site and replicate similar models worldwide, are responsible for the well-known image of scarcely sustainable contemporary large cities and megacities. Cities that are nowadays responsible for 70% of greenhouse gas emissions. For this reason, it is necessary to restore environmental conditions that could improve the health of citizens and urban liveability.

Before the city scale, it would be opportune to focus on the neighbourhood one. Operating at this scale is suitable to cope with the issues that influence the environmental quality of urban areas: green and blue infrastructures, water management (from recovery to the reduction of runoff, to the use of water as cooling strategies) and mobility. Moreover, the distance between buildings for solar access and natural ventilation has to be defined at a neighbourhood scale, not at the city scale.

A well-ventilated elevation, or a river, or the breeze to intercept when settlements are built, become recognizable elements of the places, that mark a connection with the natural elements, nowadays often neglected. The prevalent multi-storey buildings which block the natural ventilation, with large openings facing the solar radiation for many hours per day, and materials with little heat capacity unable to store solar radiation, could not be used in cities with a tropical climate. Together with this type of development, the informal settlements, developed from the spontaneous aggregation of single-family buildings, do not have a link with the environmental characteristics of the urbanized site, because they arose close to an already urbanized area or to complement it. They often arise without formalizing property rights and represent agglomerations lacking in services, such as the water and sewage network, formalized public spaces, and vegetation. In the case of excessive rain and heat, this condition amplifies the inconveniences for residents and worsens the functioning of urban infrastructures: slowing down/impeding the flow of water or preventing the generation of cool niches along a path, to remind some potential problems.

Intervening today in specific highly urbanized contexts could also represent a stimulus in the generation of new nuclei capable of encouraging different types of urban development that help reconstructing a link with the environmental variables of a specific site. For example, although the general characteristics of the climate of the different areas of Mozambique are known, it is necessary to analyse the characteristics of the specific context to intervene on it. These characteristics are responsible for modifying the energy flows and the relationships between the various elements.

Strategies leading to the improvement of environmental conditions in hot-humid climates generally requires not only the control of short-wave but also long-wave (emitted heat) solar radiation, which in urban areas is connected to the morphological configuration, to the orientation of the streets according to the solar radiation and prevailing winds, but also to the presence of shading systems, vegetation and water. Strategies for improving outdoor thermal comfort (i.e. mitigating the Urban Heat Island—UHI) in a tropical climate are related to:

- The development of urban morphology (geometry of the neighbourhood, building volume) to minimize radiation trapping and enhance shadowing;
- The development of a street layout and building shape to favour wind access (Fig. 2);

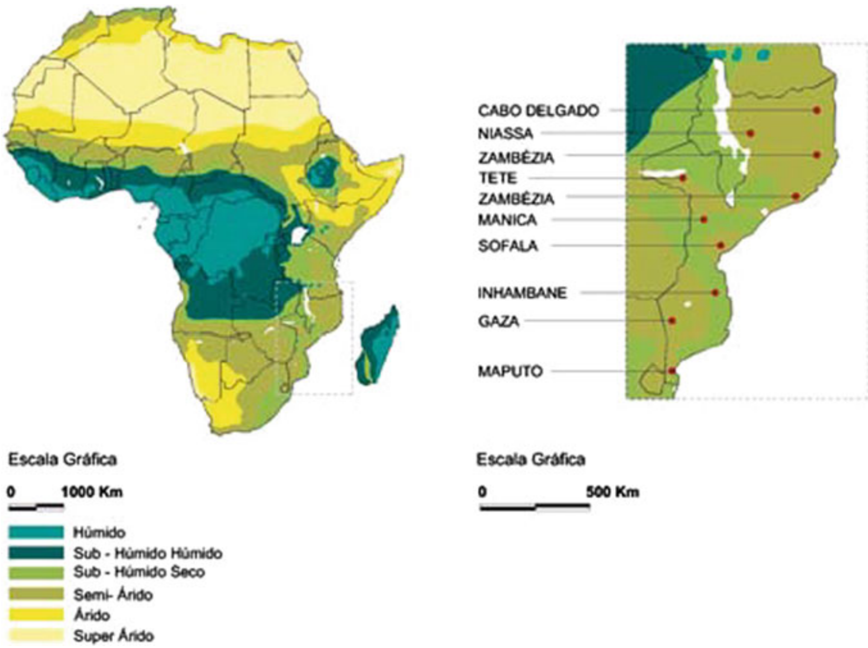


Fig. 1 Distribution of aridity zones in Africa and Mozambique (according to the World Meteorological Organization—WMO)

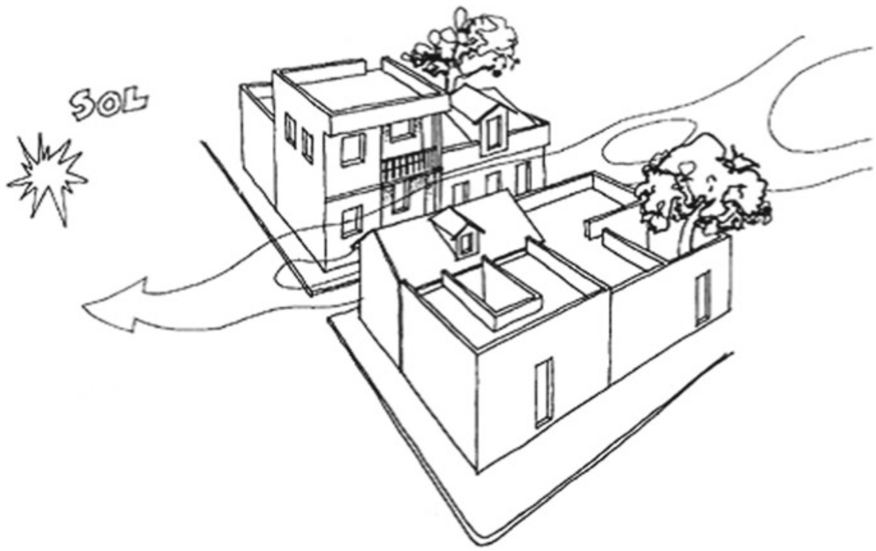


Fig. 2 Urban ventilation plays an important role both for well-being in open spaces and inside buildings, for this reason it is important to orient the streets in the direction of prevailing winds or breezes

- The control of the physical properties of urban surfaces, i.e. colour (Albedo) and thermal mass.

Increase of vegetation and—when relative humidity conditions allow—water bodies to maximize evapotranspiration loss.

As suggested by Butera (2018), for East African Community with a tropical climate (primarily if located in a latitude from about 11 °S to 5 °N), confirmed by obstruction profiles and sun charts of different types of streets, as represented in Fig. 3:

- A North–South orientation is the best. A point at the centre of the street canyon, ground level, is subject to direct sunshine for the minimum number of hours in all months; thus, better outdoor and indoor comfort is achieved, provided that the windows and walls of the upper floors are appropriately shaded with movable devices.
- With the East–West orientation, the floor of the canyon is fully exposed to solar radiation for most of the time, irrespective of the aspect ratio (H/D): only in the coolest and in the hottest month of the year the floor of the canyon will be fully shadowed for H/W $\geq$ 2. Comfort condition is complicated to reach only considering the geometry. Shading devices, vegetation and water are strongly recommended.

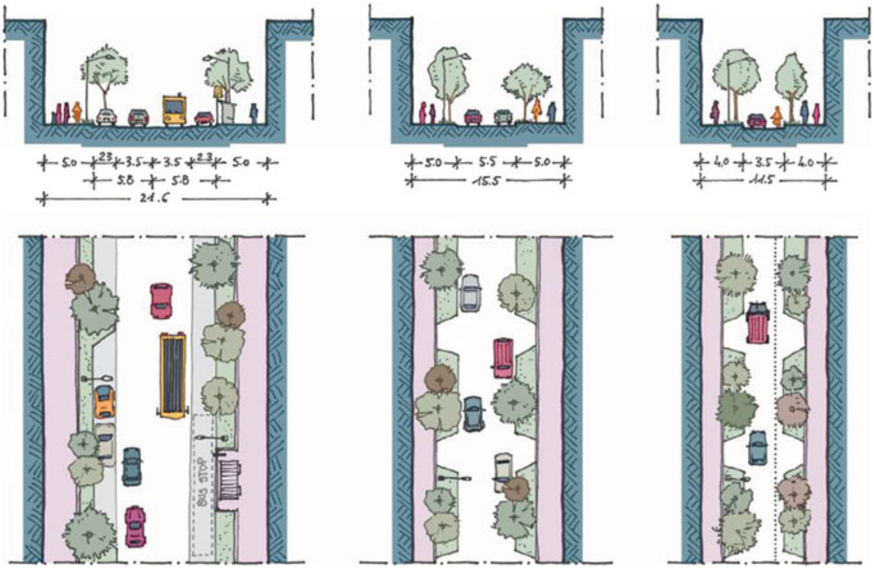


Fig. 3 Configurations of the streets according to the dimension. Left: neighbourhood connector; these streets service and link neighbourhoods. Centre: access street; to accommodate shared pedestrian, bike and vehicular movements. Right: footpath or shared path; pedestrian and cyclist street allowing temporary access to vehicles (*Credits* Butera 2018)

Urban materials and morphology determine the urban heat island, and—especially in hot climates—the albedo (linked to colour and roughness), the specific heat and density have to be taken into account.

High values of these last two characteristics guarantee the contribution of the thermal mass, i.e. the possibility to store the heat during the day and to release it in the evening, from the buildings and from the urban canopy layer (i.e. the layer of the atmosphere above the building's roof).

Massive materials (bricks, concretes, raw earth …), colours of the cladding of buildings and non-dark urban flooring are suitable to avoid heat absorption. Moreover, as far as urban flooring is concerned, it is also essential to guarantee a good percentage of pervious materials (soil, mixed flooring, partly sealed pavements and soil).

Vegetation (in particular, trees) has multiple benefits concerning both the mitigation of the causes of climate change (absorption of CO_2) and adaptation to the climate changes, linked to the reduction of the urban heat island, which also represents an improvement of thermal comfort and a contribution to the management of excess rainwater. Trees represent a contribution at least for four reasons:

– shadow on people;
– shadow on urban surfaces, which reduces the risk of surfaces overheating;
– reduction of the air temperature values;

– reduction of the mean radiant temperature (parameter considered in calculating the thermal balance, i.e. thermal comfort).

However, it is important to emphasize that the increase of vegetation is possible if the water resource is adequate. In tropical climates with a concentration of rainwater in the rainy season, it is recommended to implement water collection systems not only at the building level but also at the urban space level to have available water to irrigate the vegetation.

The generation of new urban spaces and the renovation of existing ones in consolidated urban fabrics is fundamental for the connection of natural elements, in particular greenery and water. They allow for walking and staying in areas protected from intense solar radiation and control the flooding and excess rainwater on streets, directed on predetermined routes and not in the areas occupied by buildings. A balance between permeable and impermeable surfaces is therefore important.

4 Bioclimatic Strategies for Architectural Design

Outdoor comfort, which is strictly affected by the local climate, also determines indoor comfort, which, in turn, is the driver of the energy consumption deriving from the need for heating or cooling.

Before focusing on the building and the systems to optimize indoor thermal comfort conditions, it is important to evaluate the connection with the surrounding area and, whenever possible, the elements concerning the choice of the place, the orientation and the shape of the building, because they affect the energy flows exchange between the environment and the inhabited space.

As described above, the orientation of the streets and the buildings are important in urban areas. Orientation is referred to solar radiation exposure and, especially in hot humid climates, to prevailing winds. Even in a warm climate as in the Mozambican one, it is fundamental for the development of the houses to consider the wind regime, adequate ventilation and the consequent improvement of comfort indoor, as developed in the project of Condominio do Caracol in Maputo designed by Josè Forjaz (Fig. 4). Optimizing the orientation is possible to avoid overheating situations, which is the first step towards promoting heat protection and dissipation strategies.

For the Mozambican territory, the best orientation for the main facade is the North, with a deviation that must not exceed 45º from the north.

With this in mind, the sizing of the glazed areas must be compatible with the orientation of the facade; the kitchen space must be the coolest in the house, having its heat production, and therefore cannot be oriented to the west. The best orientation to reduce heat gains from solar radiation will be the development along the East–West axis, limiting the exposure area of the east and west facades.

When the solar radiation reaches the north-facing facade, it reaches a very high angle and can be easily shaded while ensuring good lighting. In urban situations where the choice of orientation usually is impossible, it can be compensated by

Fig. 4 Condominio do Caracol at Maputo. A residential building that include different strategies to limit overheating indoor. In particular, the most important strategies implemented are: Integration of planted areas on all exterior surfaces of the houses, an adequate orientation, the cross-ventilation, the shading device for the openings (*Credits* Forjaz 2011)

strengthening other strategies suitable for controlling solar gains, such as the shading of walls and windows and their sizing (Fig. 5).

In terms of building shape, the configuration and layout of the interior spaces—depending on the function—influence the exposure to incident solar radiation and the availability of ventilation and natural lighting. A compact building will generally have a relatively small exterior wall, i.e. a low surface/volume ratio. For small- and medium-sized buildings, this situation can offer advantages because the heat exchanges with the surrounding are limited, but, at the same time, it could be limited and the possibility to have cross-ventilation.

A fundamental role is played by materials with high thermal mass, as already mentioned, with the possibility to store heat during the hot hours of the day. Depending on the type of material and the thickness of the element, the release can be after hours, in particular in the evening, when the outdoor temperature begins to drop. They can be external walls, internal partitions, flat roofs or a green roof (Fig. 6). Also in traditional architecture, currently used out of the cities, as in the example of the school in Capo Delgado (Fig. 7), is possible to implement strategies that improve thermal performance of the buildings.

Direct solar radiation is by far the primary energy source that heats the building. For this reason, cooling strategies must be accompanied and anticipated by measures that reduce the risk of overheating, as in the school designed in 2010 by the architects Ziegert Roswag Seiler, with the aim to preserve and improve the local architectural tradition, using renewable resources such as earth and bamboo, managing to provide

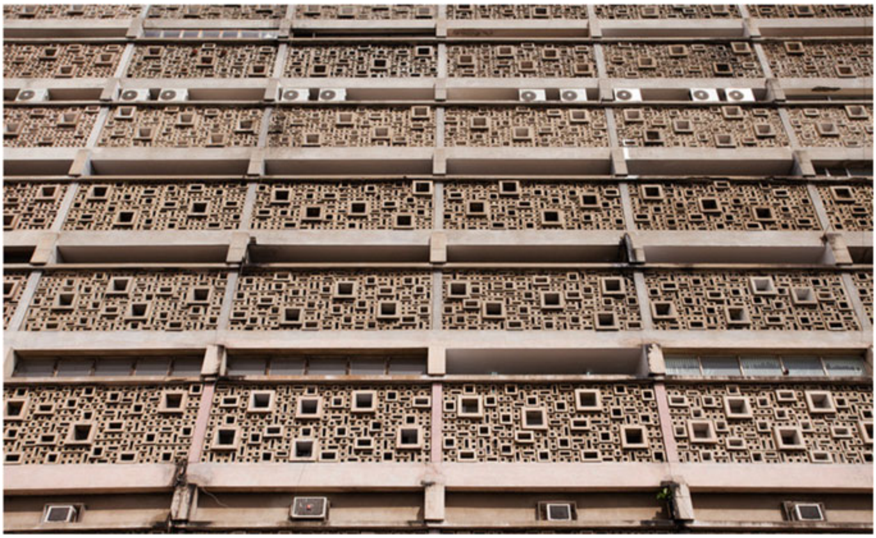


Fig. 5 Abreu, Santos and Rocha building in Maputo (1953–1956) designed by the architect Pancho Guedes. The shading of the loggias of the individual lodgings is resolved through a composition of brise-soleil which also allows ventilation (*Credits* Forjaz 2011)

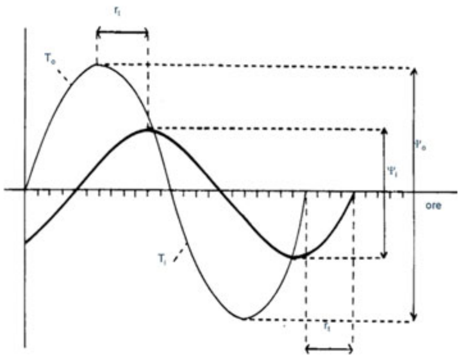


Fig. 6 The graph compares air temperature and the surface temperature of material with high thermal mass. It is possible to observe that the use of massive material helps to reduce indoor air temperature and to shift the peak hours later, according to the material and thickness Credits M. Grosso

a good internal temperature and regulate humidity (Fig. 7). First, it is appropriate to define systems that prevent solar radiation from reaching the interior of the building, in particular:

- large projecting roofs for shading the external walls and windows,
- horizontal protrusions (along the north side) and vertical (on the east and west sides),
- light colour for the facades to reflect the radiation before it passes through the outer wall,
- light roofs to allow micro-ventilation of the roof structure and

Fig. 7 A series of strategies combined in a single building, a school in Capo Delgado, in the northern part of Mozambique: massive masonry, a large roof to protect masonry and openings from solar radiation, large openings for natural ventilation, the presence of arcades for carry out part of the activities outdoors, light cover to allow micro-ventilation of the structure (*Credits* ZRS Architekten Ingenieure, *Photo* Paula Holtz)

– alternatively, massive structures and roofs, such as green roofs and green walls to increase the heat storage.

In any case, as far as possible, the space around the building should also be involved in the control of the internal microclimate. The use of vegetation, water and other shielding elements can help a lot, regardless of the strategies implemented in the envelope and the elements that configure the building.

Strategies aimed at dissipating the heat produced inside the building (free earnings from electrical equipment, people, stoves…) are based on what is called "thermal wells". These techniques avoid overheating, bringing the internal temperature values to levels near to or even lower than the external air temperature (Fig. 8).

The best design solutions for passive cooling combine different strategies to achieve greater efficiency, such as heat dissipation through night ventilation of the heat re-emitted by the massive element (external wall, roof, floor).

The effectiveness of passive cooling techniques can often be improved through the use of systems that work with energy from renewable sources, such as solar or photovoltaic panels, or systems with low energy consumption from non-renewable sources, such as fans (Fig. 9).

In the Mozambican climate context, it is possible to balance the building and the climate by applying a series of design strategies deriving from the bioclimatic approach, well known in the vernacular and popular building systems, which can also be reinterpreted for contemporary architecture. Today, these traditional techniques are enhanced with the technological knowledge currently available and optimized so that they can be successfully incorporated into the design and operation of buildings. These strategies and techniques allow buildings to adapt to the surrounding environment through architectural design and the conscious use of materials and

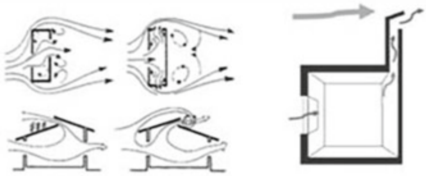
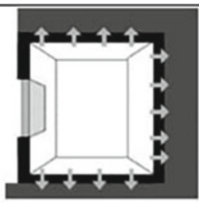
Air that allows the natural ventilation (cross ventilation and from chimney effect)	
Water vapour for evaporative cooling (direct and downdraught)	
The night sky for the nocturnal re-irradiation	
Ground for the underground geothermal systems	

Fig. 8 A set of cooling strategies based on natural "thermal wells": air, water vapor, nocturnal sky, ground Credits M. Grosso

construction elements, avoiding (passive architecture) mechanical systems based on energy, often derived from non-renewable sources.

The existing building, that can be placed within a consolidated and/or compact urban fabric, offers reduced possibilities to react to the excesses of the climate compared to the design from scratch of an artefact born from the correct interpretation and enhancement of environmental, climatic and site parameters. Intervening on existing buildings, even if limited to a few elements, always depends on the type of building and on the social context. Therefore, it is essential to activate participation processes with the inhabitants who can identify the potential for improvements. A single-family building in an informal context could be renovated by modifying the envelope, increasing the roof surface to improve shading both inside the building and the external walls of the space around the building. The presence of plants could

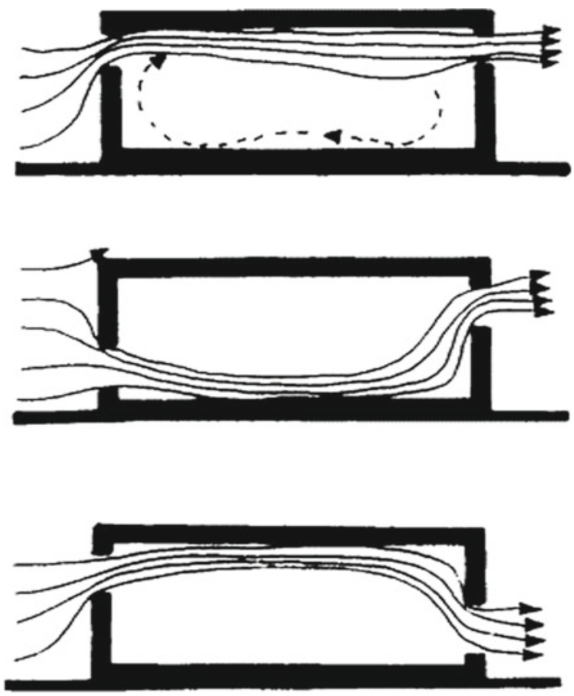


Fig. 9 The combination of cooling strategies that increases the effectiveness. In this case the thermal mass is associated with the natural ventilation that removes the heat from the building surfaces and moves it outside from the openings Credits M. Grosso

shade the roof and the external areas around the house and the possibility of collecting and reusing rainwater that could also be used for irrigation.

A multi-storey residential or office building can be modified, especially in terms of envelope and roof. A ventilated façade on an existing envelope could provide micro-ventilation and shading of the wall. Shielding systems of the openings to the outside could guarantee the passage of air and shield the solar radiation, along with mobile screens, or part of the facade itself, as in the already mentioned case of the screening of the loggias in the Abreu, Santos and Rocha building in Maputo (Fig. 4).

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