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Sustainable Building Design in Kenya

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Abstract

Sustainable design strategies involve complex interactions among social, economic and environmental factors those should be analyzed and solved quite differently by heterogeneous disciplines and stakeholders involved. Focusing on the cities of developing countries in tropical regions, characterized by fast urban population growth and a staggering increase in the energy consumption for building sector, it emerges that appropriate active strategies and building energy optimizations are promptly recommended. For this purpose, in the present work, energy evaluations were carried out for the designing of a residential building in Nairobi, Kenya, considering different strategies and solutions, taking into account also the affordability and considering the possibility to push local based economies through the use of built-on-site materials. This strategy may lead to a significant cost reduction and energy saving due to lower construction costs and in addition also a lower embodied energy of the building materials. Furthermore, in a region understudy, characterized by unstable economic security, the employment of local labor forces may lead to the formation of local based economies.

Keywords: *Sulstainable building design; energy performance; economic analysis;East Africa*

1. Introduction

Majority of the world's population today lives in cities, with over 863 Million of people living in slums and informal settlements [1] characterized by also low quality of electric supply service [2]. In this respect, some researches which address the prevailing lack of electricity access are already developed [3-5]

However, urban populations are continuing to grow at a rate faster than the cities can manage, leading to serious problems on infrastructure and other services like housing. If current development trend will continue, the global area of urbanized land could be tripled in 2030 with respect to 2000 [6]. Almost 90% of the global urbanization between now and 2050 will take place in countries of the developing world, mostly located in tropical/subtropical regions [7]. By the end of the current decade Eastern Africa urban population will be increased by 50% and the total number of urban dwellers in 2040 is expected to be five times with respect to 2010 [8].

Urban areas are responsible to about 70% of global energy use and energy-related GHG emissions, thus cities in the developing world [9], where most of the growth will take place in future, will have a significant impact on GHG emissions, seriously threatening any effort to reduce them – unless new urban

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developments are designed to minimize their impact. New urban development design is a key issue for coping with global warming. An appropriate urban and building design may lead to very low emission cities if properly designed [10-12]. UN-Habitat estimates that African cities become home to over 40.000 people every day [13]; considering that Nairobi is one of the biggest cities in East Africa with an estimated population of over 3.2 Million people [14] and a projected growth of 14 Million by 2050 and 38 Million by 2100 [15], a strategic intervention is essential among all also in building sector. Despite increased levels of urbanization, only 35.000 new homes are built in Nairobi against a demand of 120.000 housing units per year [16]. The result of this mismatch has led to increased housing prices and continued emergence of slums and informal settlements resulting to 60% of the city's population living in the informal settlements [17]. The present work hence focuses on the development of a design methodology, in order to identify critical aspects and intervention strategies for the creation of sustainable and affordable residential building in developing countries. In this framework, multi-criteria evaluations and a specific design methodology have been developed and applied on a case study building in Nairobi considering different strategies and solutions, taking into account energy performance and affordability and also considering the possibility to push local based economies through the use of built-on-site materials.

2. Methodology

Sustainable building design requires considerations about all three sustainability dimensions: environmental, economic and social. However, due to the massive urban development ongoing in developing countries, in order to avoid a dramatic increase in energy consumption and consequently GHG emissions, one of the main goals for designer is the reduction of building energy consumption and this challenge will require a radical transformation in building design procedure. For such reasons, the methodology proposed in the present work, although is more focused on the energy issue, also include the economic and social aspects. More in detail the methodology is divided into three closely interconnected thematic areas (Fig. 1). The first area focuses on the analysis of the climatic context and economic and social constrains, which allow the definition of the main principles and guidelines to be used during the concept design of the building. Subsequently, the energy consumption of different building configurations, characterized by different type of envelope, derived from the principles identified in the previous step, have been compared and the optimal solution in terms of energy savings have been selected. Finally, the selected solution has been verified in the third step, based on economic feasibility analysis through the estimation of the final construction cost and the building operating costs.

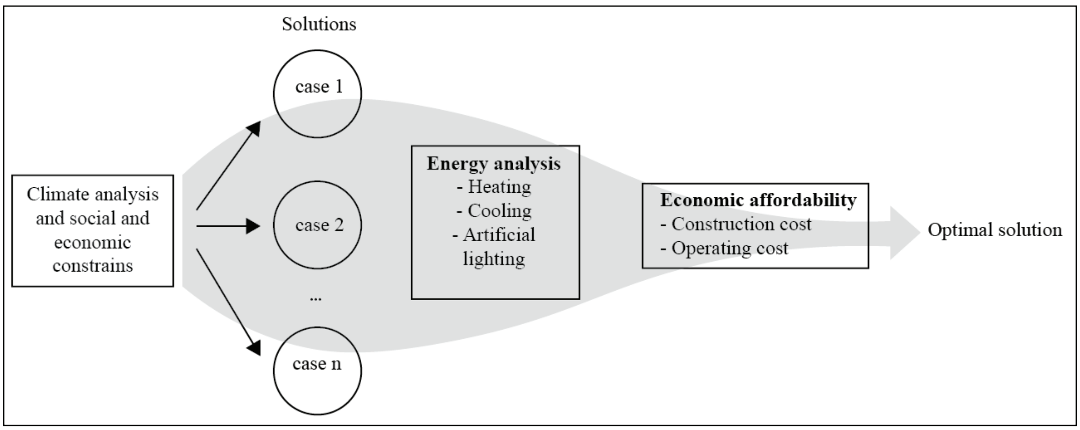

Fig. 1. Flow chart of the methodology

3. Case study building

The proposed methodology has been applied and verified on a low-rise residential building located in Nairobi, preliminary designed after a climatic analysis and a socio-economic study of the local constrains [18]

The designed building (Fig.2), which can be considered a case study, is a four storeys building and has a rectangular shape (57.04 m x 8.75 m).

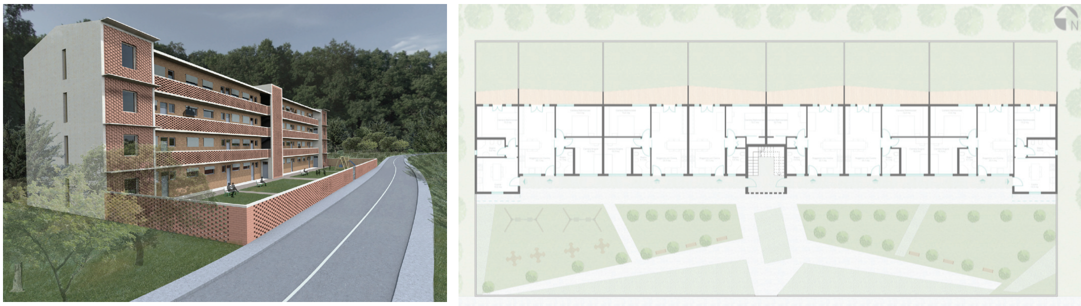

Fig. 2. Rendered view of the designed low-rise residential building and typical floor layout

The building is oriented with the main axis in the east-west direction in order to better control the solar gain during the hottest hours of the day and consists in 28 apartments ranging from one to four rooms, with a total floor area of 1600 m^2.

The building shape also responds to the need of space optimization; it consists in several different typologies of apartments and one efficient space distribution system, which contribute respectively to improve the social mix and to decrease the final building cost.

The main climatic data for the reference site is shown in Table 1. The climatic data were taken from the Typical Meteorological Year (TMY) of Meteonorm database.

Table 1. Reference climatic parameters

Site	Nairobi
Latitude	01°17'S
Heating Degree-Days (18.3°C baseline)	104
Cooling Degree-Days (18.3°C baseline)	523
Max. temp. [°C]	29.0
Mean temp [°C]	17.9
Min. temp. [°C]	6.9
Annual global irrad. on horiz. Plane [kWh/m^2]	2169

3.1. Energy analysis

The energy consumption of the case study building have been evaluated for 8 different envelope's configurations and strategies as summarized in Table 2. More in detail, the configurations were selected according to a progressively iterative process starting from a base case (case 1) realized with traditional and cheap material, further variations on the building envelope and strategies were carried out and the related energy consumption and operating cost (energy bills) were evaluated. This iterative process based on try and error logic has the aim to minimize the overall energy consumption of the building.

Table 2: Case studies - building configurations

		Thermal Transmittance [W/m²k]	Thermal Phase Shift [h]	Characteristics			Thermal Transmittance [W/m²k]	Thermal Phase Shift [h]	Characteristics
Case 1	Wall	1.214	8h 11'	Base case	Case 2	Wall	0.53	10h 12'	Case 1 + insulation
	Windows	5.5	-			Windows	5.5	-	
	Roof	0.352	8h 42'			Roof	0.352	8h 42'	
	Floors	1.385	9h 00			Floors	1.385	9h 00	
Case 3	Wall	0.53	10h 12'	Case 2 + insulated window	Case 4	Wall	1.214	8h 11'	Case 1 + horizontal shading
	Windows	2.72	-			Windows	5.5	-	
	Roof	0.352	8h 42'			Roof	0.352	8h 42'	
	Floors	1.385	9h 00			Floors	1.385	9h 00	
Case 5	Wall	1.214	8h 11'	Case 4 + Shading on the Roof	Case 6	Wall	1.214	8h 11'	Case 4 + No Ventilated Pitched Roof
	Windows	5.5	-			Windows	5.5	-	
	Roof	0.352	8h 42'			Roof	0.366	2h 00'	
	Floors	1.385	9h 00			Floors	1.385	9h 00	
Case 7	Wall	1.214	8h 11'	Case 4 + Ventilated Pitched Roof	Case 8	Wall	1.214	6h 44'	Case 5 + Cross Ventilation
	Windows	5.5	-			Windows	5.5	-	
	Roof	2.84	0h 55'			Roof	2. 84	8h 11'	
	Floors	1.385	9h 00			Floors	1.382	9h 00'	

The energy consumption was evaluated using Energy Plus software, which represents a widespread and accepted tool in the building energy analysis community around the world [19-21]. This software is particularly appropriate to simulate dynamic behavior of buildings characterized by high thermal inertia, such as common in hot and tropical climates.

Simulations were performed with a set-point of 20 °C (winter) and 26 °C (summer) during the whole year according to comfort zone of Givoni Bioclimatic Chart [12]; internal loads, excluding artificial lights, were set equal to 4 W/m^2 considering a constant people occupancy throughout 24 hours. The peak artificial lighting power density was set to 10 W/m^2 from 08:00 to 22:00 throughout the year, assuming efficient LED lamps with an efficiency of 120 lm/W with the presence of dimmers. The overhead lights dim continuously and linearly in order to provide the required illuminance level set to 300 lux. Moreover, simultaneously a reduction factor equal to 0.5, which take into account the fact that not all the artificial lights of the building are switched on at the same time, have been used for the simulations.

The building is equipped with an air-to-air electric heat pump with a coefficient of performance (COP) equal to 2.3 and an energy efficiency ratio (EER) equal to 2.5 at reference conditions for heating and cooling purposes.

The final electric consumption and related operating cost due to heating, cooling and artificial lighting are reported in Fig. 3. The operating costs have been calculated considering an estimated value for electricity equal to 0.18 €/kWh according to current market prices in Kenya [22,23].

The base case configuration (Case 1) consists of a building realized with opaque walls with a U-value of 1.21 W/m^2 K realized with interlocking stabilized-soil bricks and single glazed windows with a U-value equal to 5.5 W/m^2 K. The concrete flat roof has a 10 cm thermal insulation layer and a U-value of 0.352 W/m^2 K.

According to the reported data, the annual cooling energy consumption of the analyzed building is 7.3 kWh/m^2 with no heating energy consumption, while the electrical consumption due to artificial lighting is equal to 3.2 kWh/m^2.

In order to evaluate the energy performance related to the use of more advanced building materials and construction technologies, an additional insulation layer (Case 2) and double glazing windows (Case 3), was progressively applied to the base case. However, as shown in Fig. 3, a more insulated building results in a higher cooling energy consumption respectively of 8.9 kWh/m^2 y (Case 2) and 12.7 kWh/m^2 y (Case 3). Moreover, the use of double glazing, characterized by lower visible transmittance than single glazing, increases the consumption due to artificial lighting from 3.2 kWh/m^2 y to 3.6 kWh/m^2 y.

The next configuration simulated is based on the use of an external shading system for the base case. More in detail, the use of a 1.2 m horizontal balconies in South facade and 1.5 m horizontal and vertical ledges in the North façade (Case 4), involves a reduction of the overall energy consumption equal to 40% in comparison to Case 1. However, it should be noted that although the energy consumption due to cooling decreases from 7.3 to 1.1 kWh/m^2 y, the artificial lighting consumption increase from 3.2 to 5.15 kWh/m^2 y.

The shading system can be considered, hence, a favorable solution for tropical climates even in term of operating cost, which decreases from 1.8 €/m^2 y (Case 1) to 1.2 €/m^2 y (Case 4).

Starting from this configuration (Case 4) the impact due to roof materials and types on the building performance have also been investigated in case 5, 6 and 7. In the following configurations the energy consumption due to artificial lighting is almost constant and equal to 5.15 kWh/m^2 y.

In detail, a building able to avoid the direct solar radiation on the roof and the use of an aluminum reflective layer (infrared absorption coefficient equal to 0.1) on the top of the flat roof (Case 5) leads to a reduction of cooling consumption equal to 31% in comparison to Case 4.

In Case 6 a pitched roof with tilt angle of 15°, realized with lightweight materials characterized by low thermal capacity results 10% higher consumption for cooling in comparison to the previous configuration (Case 5), so it has been discarded.

Finally, in Case 7 a double leaf roof is analysed, where the heat between the ceiling and the roof is removed by the airflow passing the roof space through openings facing the prevailing winds. In this configuration, the ceiling is realized same as the roof of Case 1, while the pitched roof consists in a wooden lightweight tilted structure with a U value of 2.84 W/m^2 K and thermal phase shift of 0h and 55'. Such configuration leads to an energy saving of 26% if compared to Case 5.

The roof analysis shows that a simple pitched roof with low thermal mass and low thermal transmittance is not a suitable solution in the reference climate, in comparison to a flat roof with a shading system. A double leaf roof configuration, on the contrary, might be an optimal solution, also for the use of a renewable energy system (photovoltaic system) for on-site energy generation, able to cover the whole electrical consumption of the building.

The introduction of natural ventilation parameter (Case 8) applied to the latter case, leads to a further energy saving of 18%. This configuration can be considered the most effective both in term of energy saving and operating cost.

All the analysis and the considerations previously discussed, brings toward the optimal configuration for the designed building type and for the tropical climate of the city of Nairobi (Fig. 3).

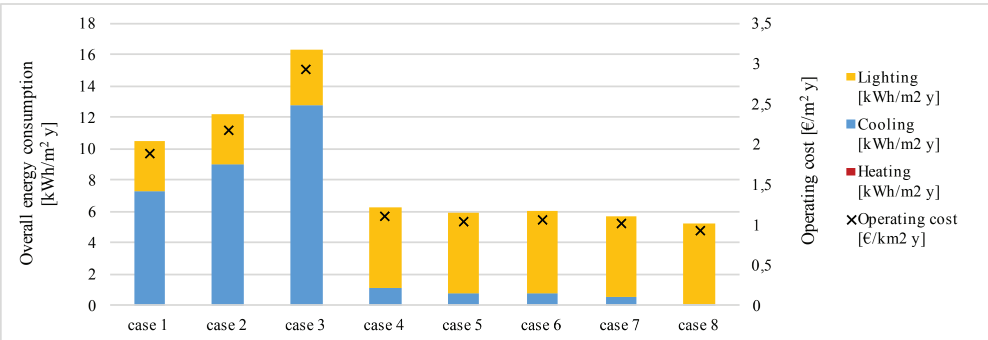

Fig.3. Overall energy consumption and operating cost

Further, in order to transform the building from energy consumers to net energy producers, the use of a PV system is considered. The PV system has been sized in order to cover all the electric consumption due to cooling, artificial lighting and also consumption related to domestic appliances, such as refrigerator, freezer and television, which can be estimated on average to 20 kWh/m^2 y. For such reason, estimated overall electric consumption of the designed building equal to 42,000 kWh/y, a PV plant with a peak power of 27 kW can provide all the required energy, to convert the building into a net zero energy building (nZEB).

3.2. Economic Analysis

According to the previous simulations, in the present section, economic analysis will be focused only on Case 8, which is most effective configuration in terms of energy savings. The economic issue has been analyzed through an accurate appraisal of the final construction costs. The reference prices are taken from the Construction Costs Handbook published by the Ministry of Public Works of Kenya in 2013 [24].

In order to optimize the building construction cost and to support the development of the local micro-economy both the use of built-on-site materials and the employment of the local workforce should be suggested. In particular, in the present work the use of interlocking stabilized-soil bricks [12] for the external walls and for the internal partitions have been considered. This type of brick can be constructed by unskilled workers thanks to the use of locally available special low-cost presses [12]. The detailed construction cost, report both in Kenyan currency (KES) and Euros, of the building is summarized in Table 3.

Table 3: Building construction costs

	[KES]	[€]
Excavation and foundation	4,498,925	38,305
Structure	9,012,795	76,736
Opaque envelope	4,790,002	40,783
Transparent envelope	2,874,060	24,470
Finishes	5,643,366	48,049
Labor	8,045,745	68,503
HVAC system and PV plant	16,332,033	139,053
Land	3,486,489	29,685
Infrastructure	3,486,489	29,685
Professional fees	3,486,489	29,685
Contingencies	1,743,245	14,842
Finance charges	1,743,245	14,842
Company profit	6,514,288	55,464
Total cost	71,657,172	610,101

The construction cost of the building including equipments have been estimated equal to 439,000 €. However, the additional cost related to the land, infrastructure, finance charges, professional fees and other contingencies have been added as a percentage (40%) of the latter cost according to African Development Bank Group informal survey of developers [24] as well as the cost due to the company profit, equal to 10% of the total amount. In this respect the overall specific cost is estimated about 380 €/m^2. Such value lies in the range of standard selling price of flats in Nairobi which ranging from 300 €/m^2 to 490 €/m^2 [24]. Hence the proposed solution can be considered competitive and more cost-effective than the actual building construction

4. Conclusions

The design methodology developed in the present work and applied to a case study residential building in Nairobi has shown the possibility to realize a net zero energy building (nZEB) with a competitive local selling price. Furthermore, in a context, characterized by unstable economic security, the construction of well-designed building would be able to push the local based economies through the use of built-on-site materials as well as the employment of local labor forces. In the considered climate, passive heating and solar energy can be used in order to improve comfort and reduce, or even eliminate, any need for a heating system. The use of wall without insulation, characterized by medium thermal mass along with the use of moderate ventilation is also suggested.

5. Copyright

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Biography

Fabrizio Leonforte is a research fellow at Department of Architecture, Built environment and Construction engineering. He has carried out different theoretical and experimental works on renewable energy and energy efficiency in buildings. He has been also involved as advisor in national and international researches as well as in different project with NGOs and Universities for capacity building of local staff.