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Reducing thermal discomfort and energy consumption of Indian residential buildings: Model validation by in-field measurements and simulation of low-cost interventions

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ABSTRACT

The study proposes and compares low-cost strategies to improve the quality of existing building stocks, with special regard to a widespread Indian residential typology. A dynamic energy model of this particular local building typology was simulated with Energy Plus software and validated by comparing it with some original *in situ* measures, recorded by hourly step. The validated model was used to simulate a selection of low-cost and technically simple interventions, whose effects on the energy performance and indoor comfort were compared to the baseline case study. Comfort performances have been evaluated using comfort indoor degree hours (CIDH) and the TSI index. A combination of the most effective solutions was proposed and simulated. The results were used to assess possible improvements of comfort (reduction of CIDH) and savings of energy consumption (referred to an A/C scenario). Finally, the role of occupants' behaviour was further investigated.

1. Introduction

Cities are part of the energy consumption and climate change problems, but they are also a key part of the solution. Cities consume (without producing) the vast majority of global energy and are therefore responsible for large of greenhouse gas emissions [1]. On the other hand, they can greatly help to make the economies demanded by the coming decades. They can propose global approaches to reduce the environmental footprint. They can test and spread good practices and propose innovative solutions.

In India increasing interest and attention are devoted to urban planning strategies meant to guide and regulate energy and environmental issues. One virtuous example is represented by the Sustainable Development Action carried out by the local Municipal Corporation of Thane (TMC) in Maharashtra. At the architectural scale, the Torrent Research Centre building in Ahmedabad [2] inaugurated a fertile season of experimentation and construction of sustainable and green buildings, passive solar buildings [3], frequently certified by LEED [4] or other labels.

However, the rare "best practices" examples are not keeping pace with the ferocious rhythm of production of common architecture showing climate-inadequate characteristics. The residential building sector appears to be the third energy consumer in India [5], but its importance is expected to rise due to the growing rate of urbanization and equipment. At today, the largest part of construction is qualitatively poor, as the traditional and local knowledge is quickly disappearing and the highly innovative and strongly interesting new sustainable technologies are rarely applied. Most residential buildings respond to the same typology, with thin walls, lack of shading systems, and lack of insulation, especially on the roof. They are vulnerable to high tropical temperatures and to extreme climate events. At the same time, they are the target of a rising demand of better levels of thermal comfort coming from the middle-classes. For that reason, they are quickly shifting toward a total dependency on air conditioning (A/C) with consistent effects on energy consumption, health and urban climate (UHI) [6–9].

In this paper, it was aimed to explore alternative solutions to total A/C dependency of residential building for a tropical Indian city, testing through simulation the effect of low-cost and technically simple interventions on comfort and energy consumption.

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Nomenclature

T_g	globe temperature (°C)
WBT	wet bulb temperature (°C)
V_a	air velocity (m/s)
T_c	comfort temperature (°C)
T_o	daily mean outdoor temperature (°C)
T_{in}	indoor temperature (°C)
T_{ext}	outdoor temperature (°C)
T_{olt}	monthly mean outdoor temperature (°C)
T_{rm}	running outdoor mean temperature (°C)
T_{outrm}	ASHRAE's running outdoor mean temperature (°C)
PMV	predicted mean vote
cPMV	corrected PMV
CIDH	cooling indoor degree hour CIDH = $\sum (T_{\text{in,op}} - T_c)$
$T_{\text{in,op}}$	indoor operative temperature (°C)
TSI	tropical summer index

2. State of the art

2.1. Climate-responsive residential buildings in the tropics

Tropical hot-humid climate shows one of the most demanding and complex weather that architecture and urban planning have to deal with. Buildings have to be comfortable in heat and damp conditions. To date, more than 40% of Earth's population live in the tropics, with an increasing tendency. Many big cities are located in tropical areas, such as Mumbai, Rio de Janeiro, Kolkata, Jakarta, Lagos, Singapore. In a climate change scenario, extreme events are expected to become more likely in tropical areas [10]. Studies on long-term trends in several Indian tropical cities such as New Delhi, Kolkata and Mumbai show that warmer and colder days have become more frequent [11].

In the past, traditional and local architectures of tropical areas were carefully designed to be climate-responsive, reduce thermal discomfort and mitigate the impact of catastrophic events such as heavy monsoon rains. Building orientation, structure, materials and strategies depended on transmitted expertise tailored to the specificities of the local context [12]. In the last decades scientific research has shown an increased interested in these traditional constructive forms worldwide [13,14] and for specific climates, notably the tropical one [15–20]. Traditional solutions are presented as examples of climate-responsive architecture.

These studies go hand in hand with other work proposing adapted criteria to build contemporary tropical climate-responsive buildings [15,21,22], very frequently coupling lessons coming from local traditions with new approaches based on contemporary technologies and materials.

Recent research accords an important role to the study of specific issues of tropical residential buildings, such as natural ventilation, cross ventilation, orientation, solar radiation, rooftop insulation, materials [23–26]. Many of them use simulation tools to test and compare different solutions [27,28].

Nearly the totality of those studies is concerned with solutions for new buildings and new constructions. Retrofit and rehabilitation still remain largely unexplored and call for deeper investigation. In the context of this paper, we mainly refer to [29,30] and to previously quoted studies for methodology and identification of solutions.

2.2. Energy consumption and thermal comfort issues in residential tropical buildings

The recent literature has devoted large amounts of attention to energy consumption issues related to buildings in the tropics. These mostly refer to offices [31], institutional, commercial and public buildings, such as schools and universities. Residential buildings have not been left out of the picture altogether [32,33] but still require consideration. Many topics have been dealt with, such as life-cycle energy assessments [34–36], occupants behaviours and practices [37,38], and uses and regulation of A/C [6,39–41]. The dissemination of A/C in tropical areas is a particularly important topic. In these areas the use of energy to cool houses and apartments is not common yet but it is increasingly becoming so [42]. Such a trend is expected to have a major influence on the total energy demand to control indoor temperatures. That is one of the reasons why in tropical areas energy issues are strongly linked with thermal comfort studies.

Concerning thermal comfort, many studies are mainly based on fieldwork carried out in tropical countries [40,43–48]. Moreover, general studies and review on comfort models and adaptive thermal comfort are reported in Refs. [49–54]. As regards the approach adopted in this paper, it was decided to focus on a developing research field coupling thermal comfort, energy consumption, occupants' behaviours and architectural issues in tropical areas. The studies pertaining to this approach [38,55–57] conceive the buildings as a complex and dynamic system in which where technique, human behaviours and space characteristics interact and need to be considered together in order to evaluate strategies to reduce energy consumption and thermal discomfort. General studies and review linking comfort and reduction of energy consumption are reported in Refs. [58,59].

2.3. A focus on the city of Kolkata, India

Until the first half of the 20th century, design of residential buildings in Kolkata never forgot the lessons coming from tradition. Houses were first built in brick, with lime-brick, dust mortar and later on with cement-sand mortar, but the thickness of the walls, the shading systems (as the verandas or the porches), the courtyard and the insulation of the roof were the shared guidelines for a climate-responsive architecture [15]. Colonial houses followed that model: the influence of various styles (neo-classicism, neo-baroque, revival, modernism, liberty) certainly modified the decoration and the external appearance of the buildings, but the basic principles continued to be applied. During the last seventy years, Kolkata had to deal with traumatic events. Famine (1943) and political partitions after bloody struggles (1947; 1972) drove thousands and thousands of people to come to the city. That led to an intensified necessity of building quickly and at low cost and represented for Kolkata a first breaking point from the traditional constructive systems. Some high quality neighbourhoods were built, especially in the 1960s and 1970s, with massive walls, verandas, vegetation, shading systems, but the standards have unstoppably started to fall down. In recent decades the economic pressure, the development rate, the industrialized-cement based technology, the growing prices of free land, the exploitation of every centimetre of building surface have led to the creation of a dense and qualitatively poor architecture, quickly shifting to a complete dependence on air conditioning. The penetration of AC in the Indian context is one of the most worrying problems related to energy consumption.

3. Objectives and methodology

This study proposes low-cost strategies to improve the quality of a widespread Indian residential building typology. The