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Energy modeling of urban informal settlement redevelopment: Exploring design parameters for optimal thermal comfort in Dharavi, Mumbai, India

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HIGHLIGHTS

- Propose a framework to explore design parameters of informal settlement redevelopment.
- Demonstrate need for assessing thermal comfort implications in developing world cities.
- Explore 18,900 design scenarios for largest settlement in Asia (Dharavi, Mumbai, India)
- A vertical form was most desired design with WWR, ventilation important parameters.
- Highlight comfort equity issues and underscore the need for an informed design process.

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ABSTRACT

Cities are of paramount importance to meeting our sustainable energy goals. In particular, the massive informal settlement or "slum" redevelopment programs occurring in many global cities of the developing world represent an incredible opportunity to design dwellings that improve living conditions while putting us on a trajectory towards more energy efficient cities. However, we currently lack an understanding of how redevelopment designs will impact occupant aspects like thermal comfort and energy usage. In this paper, we explore how early-stage design decisions for redevelopment of informal settlements would impact thermal comfort and energy implications in a highly contextualized energy simulation. Specifically, we conduct a first-of-its-kind analysis of the Dharavi informal settlement in Mumbai, India that identifies optimal redevelopment design configurations, explores spatial and temporal thermal heterogeneity and quantifies the impact that specific design parameters have on thermal comfort. In doing so, we aim to establish a novel computational energy modeling framework for exploring the impact that localized design parameters have on informal settlement redevelopment in India and the rest of the world. We model and simulate 18,900 design scenarios in the existing horizontal (M1) and two proposed vertical (M2, M3) building morphologies. Our results indicate that redevelopment plans must be designed carefully since simply replicating current materials and other parameters in a vertical form will likely worsen thermal comfort and associated energy burdens for occupants. Moreover, results revealed that the M3 vertical morphology was the most desired design case as it provided the most "compliant" days (i.e., days in which no dwelling exceeded the upper bound of Indian comfort standards) but thermal comfort equity could be an issue as significant variation exists between units at the ground floor and top floor. The M3 vertical morphology was also found to be the most sensitive form to other building design parameters (e.g., WWR, thermal insulation, ventilation) – underscoring the need for specific design guidelines on other parameters when adopting this form. Deeper sensitivity analysis revealed that window-to-wall ratio (WWR) was the most sensitive design parameter. Additionally, we found that the ventilation rate had as much of an impact on thermal comfort as other design parameters pointing to opportunities to enhance thermal comfort in the operational phase of dwellings. In the end, by establishing a computational energy modeling framework specifically for informal settlements and exploring design parameters for the largest informal settlement in Asia (Dharavi), our work has significant implications for how we can inform informal settlement redevelopment that both enhances occupant living conditions and set our cities' on a pathway to a sustainable energy future.

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1. Introduction

Cities now account for over 75% of global primary energy usage [1] and as the world continues to rapidly urbanize this share is expected to grow. Much of this rapid urbanization is occurring in the global cities of the developing world (e.g., Mumbai, Beijing, Nairobi, Jakarta, Rio de Janeiro) – enhancing the importance of urban energy efficiency for the world's long-term energy sustainability. Nearly 1 in 8 people in the world (881 million people) live in informal settlements or "slums" with the majority of such settlements concentrated in the urban developing world [2]. Such informal settlements are characterized by poor quality of life having one or more of the following deprivations: lack of access to improved water sources, lack of access to improved sanitation facilities, lack of sufficient living area, lack of housing durability and lack of security of tenure [3].

In order to improve such conditions, there has been a significant push for the redevelopment of informal settlements worldwide. Since India's independence in 1947, several policies have been put in place to eradicate or redevelop informal settlements in metropolitan cities like Mumbai. Ironically, most of these attempts were top-down and instead led to poverty recycling, generating more slums within the urban scape [4]. To tackle such proliferation of slums, in 1995, the Government of Maharashtra adopted a policy for "Slum Rehabilitation (SR)" to redevelop the slums into high-rise social housing. The slum redevelopments involved the demolition of existing slums and redeveloping them at a higher density. The increased density opened up land for market-rate housing and closed the housing deficit while facilitating *in-situ* slum redevelopment [5]. This scheme provided the slum dweller access to a cross-subsidized, free of cost house, without burdening their time or economic poverty [6]. For the first time, this SR policy dissociated the historical failure of governments to improve slums. The success of SR scheme has led the Central Government of India to adopt the same strategy across the nation as part of its *Housing for All-2020* policy.

Dharavi, located in Mumbai, is one of the largest informal settlements in Asia and is representative of this redevelopment process [4]. Dharavi is geographically located in the center of the city with an estimated population density of 870,000 people per square mile. It is estimated that Dharavi is home to more 1 million people within a span of 535 acres [7]. Historically, Dharavi grew organically near the central business district of Mumbai and presently occupies some of the city's most prime land. It has become the first stop for low-income migrants and provides the most affordable housing option in central Mumbai. Apart from housing Mumbai's labor population, Dharavi itself is an informal business hub that contributes about US $660 million to the city's GDP annually [8]. Being such an important economic hub, Dharavi is poised to have 22 million sq-ft of housing redeveloped for its current and incoming residents [9].

Given the magnitude of such redevelopment in Dharavi and the rest of the world, the energy and human comfort implications are enormous. Redevelopment decisions regarding urban and building design will undoubtedly shape urban energy demand and the thermal comfort of inhabitants for decades to come. It is well known that building design decisions impact thermal comfort and reduce building related energy usage. Moreover, recent research estimates that modifications to urban form could reduce energy usage in cities by 26% worldwide [10] – further underscoring the importance of early-stage redevelopment design decisions. Additionally, previous work [3,11,12] has pointed out that these redesigned building dwelling units are potential spaces of thermal discomfort and loss of health, asserting that the lack of a localized set of design guidelines is the primary cause for such outcomes. In this paper, we explore how early-stage design decisions for redevelopment would impact the thermal comfort of the 1 million residents of Dharavi, Mumbai through a highly contextualized energy simulation. As a result, the contribution of this work is twofold. First, we establish a novel computational energy modeling framework for exploring the impact of localized design parameters on informal settlement redevelopment in India and across the world. Second, we apply our framework to do a first-of-its-kind analysis of the Dharavi informal settlement that identifies optimal redevelopment design configurations, explores spatial and temporal thermal heterogeneity and quantifies the impact that specific design parameters have on thermal comfort.

2. Related work

A significant body of research has utilized physics-based energy simulations as the basis for understanding how early design decisions impact energy usage and thermal comfort at both the building [13–15] and urban scales [16,17]. These simulations are often based on a set of deterministic inputs and modeling assumptions, which, if defined incorrectly, can leave lasting energy and thermal comfort-related consequences – especially in low-energy buildings [14,18]. As a result, previous studies address two major aspects of early-stage building design: sensitivity of building design parameters and optimization of their values in relation to some pre-defined objective.

Previous work in this domain has shown that buildings can be sensitive to changes in specific design parameters based on the local climate. Factors including window-to-wall ratio [19,20], ventilation [21] and wall insulation [22] were among the most common parameters that affect building energy performance. Recent work utilized parametric energy simulations to study the energy impacts of various design factors for buildings in urban areas [23]. This study found that both the urban form and the specified window-to-wall ratio (WWR) had a substantial impact on simulated energy usage and highlighted the potential for such results to provide guidance to designers.

In addition to understanding the sensitivity of specific design parameters on building performance, previous works also optimize selected building parameters to achieve some pre-defined objective related to building energy consumption [23,24], thermal comfort [25] or performance robustness (referring to the ability for a building to maintain its preferred performance under uncertainty in operations and external conditions) [26]. While many of these early-stage design studies focus on optimizing building parameters for energy consumption, additional works use similar approaches to optimize for daylighting [15] and walkability [16]. Once the parameters are selected for optimization, they can either be assessed locally or globally – referring to whether they are studied one-by-one or all together [27].

While these and other previous works have provided significant guidance on designing for urban energy sustainability, the majority of such works have been focused on cities of the developed world. Even when previous research was contextualized to cities in the developing world (as done for cities in China by [23]), such work was focused on formalized neighborhoods that tend to follow similar design procedures and material properties as buildings in the developed world. As a result, there exists a substantial need to study the impact early design decisions have on energy usage and thermal comfort in the very pertinent context of informal settlement redevelopment. The importance of such contextualization has been underscored in previous work that studied the modeling of energy systems in the developing world [28].

One of the reasons designers and engineers use energy simulation tools in early design stages is to understand how a building consumes energy in order to provide services to its occupants. Often one of the most energy intensive services is to provide heating and cooling to